Astronomy & Astrophysics manuscript no. Processing
February 4, 2008

Archeops In-flight Performance, Data Processing and Map Making

J. F. Macías–Pérez [1], G. Lagache[20], B. Maffei[3], P. Ade[3], A. Amblard[4], R. Ansari[5], É. Aubourg[6,7], J. Aumont[1], S. Bargot[5], J. Bartlett[7], A. Benoît[8], J.–Ph. Bernard[9], R. Bhatia[25], A. Blanchard[10], J. J. Bock[11,12], A. Boscaleri[24], F. R. Bouchet[13], A. Bourrachot[5], P. Camus[8], J.-F. Cardoso[14], F. Couchot[5], P. de Bernardis[15], J. Delabrouille[7], F.–X. Désert[16], O. Doré[27,20,30], M. Douspis[20,10], L. Dumoulin[17], X. Dupac[25], Ph. Filliatre[18], P. Fosalba[19,20], K. Ganga[7], F. Gannaway[3], B. Gautier[8], M. Giard[9], Y. Giraud–Héraud[7], R. Gispert[20]†⋆, L. Guglielmi[7], J.–Ch. Hamilton[21], S. Hanany[22], S. Henrot–Versillé[5], V. Hristov[11], J. Kaplan[7], J.-M. Lamarre[23], A. E. Lange[11], K. Madet[8], Ch. Magneville[6,7], D. P. Marrone[22], S. Masi[15], F. Mayet[1], J. A. Murphy[26], F. Naraghi[1], F. Nati[15], G. Patanchon[2], O. Perdereau[5], G. Perrin[1], S. Plaszczynski[5], M. Piat[7], N. Ponthieu[20], S. Prunet[13], J.–L. Puget[20], C. Renault[1], C. Rosset[5], D. Santos[1], A. Starobinsky[28], I. Strukov[29], R. V. Sudiwala[3], R. Teyssier[13], M. Tristram[5,1], C. Tucker[3], J.–Ch. Vanel[7], D. Vibert[13], E. Wakui[3], and D. Yvon[6]

(Affiliations can be found after the references)

February 4, 2008

ABSTRACT

Aims. Archeops is a balloon–borne experiment widely inspired by the Planck satellite and by its High Frequency Instrument (HFI). It is mainly dedicated to measure the Cosmic Microwave Background (CMB) temperature anisotropies at high angular resolution (∼ 12 arcminutes) over a large fraction of the sky (around 30 %) in the millimetre and submillimetre range at 143, 217, 353 and 545 GHz. Further, the Archeops 353 GHz channel consists of three pairs of polarized sensitive bolometers designed to detect the polarized diffuse emission of Galactic dust.
Methods. We present in this paper the update of the instrumental setup as well as the inflight performance for the last Archeops flight campaign in February 2002 from Kiruna (Sweden). We also describe the processing and analysis of the Archeops time ordered data for that campaign which lead to the measurement of the CMB anisotropies power spectrum in the multipole range $\ell = 10 - 700$ (Benoît et al. 2003a, Tristram et al. 2005) and to the first measurement of the dust polarized emission at large angular scales and its polarized power spectra in the multipole range $\ell = 3 - 70$ (Benoît et al. 2004, Ponthieu et al. 2005).
Results. We present maps of 30 % of the sky of the Galactic emission, including the Galactic plane, in the four Archeops channels at 143, 217, 353 and 545 GHz and maps of the CMB anisotropies at 143 and 217 GHz. These are the first ever available sub–degree resolution maps in the millimetre and submillimetre range of the large angular-scales Galactic dust diffuse emission and CMB temperature anisotropies respectively.

Key words. Cosmology – data analysis – observations – cosmic microwave background

1. Introduction

The measurement of the Cosmic Microwave Background (CMB) anisotropies in temperature and polarization is a fundamental proof of modern cosmology and of the early Universe physics. Since the first detection of the CMB anisotropies by the COBE satellite in 1992 (Smoot et al. (1992)), a large number of ground–based and balloon–borne experiments such as DASI (Halverson et al. (2002)), CBI (Mason et al. (2003)), VSA (Dickinson et al. (2004)), BOOMERanG (Netterfield et al. (2002)) or Maxima (Hanany et al. (2000)) have measured the CMB angular power spectrum from a few-degrees down to sub-degree scales. However, simultaneous observation of very large and small angular scales have proved to be particularly difficult, as it requires both large sky coverage and high angular resolution. This has been achieved, first, by Archeops (Benoît et al. (2003a), Tristram et al. (2005b)) which has measured the CMB power spectrum in the multipole range $10 < \ell < 700$. Then, the WMAP satellite mission (Bennett et al. (2003)) has detected the CMB anisotropies, both in temperature and polarization.

Archeops, described in details in Benoît et al. (2002), is a balloon borne–experiment designed as a prototype for the High Frequency Instrument (HFI) of the Planck satellite. Its telescope and focal plane optics are widely inspired by the Planck design. The implementation of the measurement chains: cryogenics, optics, bolometers, readout electronics was a successful validation of the innovative design. Further the data processing

Send offprint requests to: reprints@archeops.org

⋆ Richard Gispert passed away few weeks after his return from the early mission to Trapani

was a learning process for future members of the HFI team. Archeops performs circular scans on the sky with its optical axis tilted 41 degrees with respect to the horizon by spinning the gondola at 2 rpm. This scanning, that is combined with the proper motion of the Earth, leads to 30% sky coverage in about 12 hours of flight. With a rotating gondola, the Sun above the horizon produces a dominant parasitic signal. The optimal way of avoiding this, while having the longest integration time, is by having a long duration (Arctic) night-time balloon flight.

The Archeops payload was successfully launched three times. First, from Trapani (Italy) in July 1999 (Benoît et al. (2002)) for a 4 hours test flight. Then from the Swedish Esrange station (near Kiruna at 68 deg. latitude North, just above the Arctic circle) operated by the French Centre National d'Etudes Spatiales (CNES) and the Swedish Space Corporation in January 2001 (hereafter KS1 flight) for a 12 hours flight, and finally in February 2002 (hereafter KS3 flight) for a 24 hours flight from which 12 night-hours were exploited for scientific purposes. In the KS3 flight, a stratospheric altitude of 35 km was reached, reducing significantly the contamination from atmospheric (mainly ozone) emission with respect to ground–based measurements. Additional information about the Archeops flights may be found at our web–site[1].

The Archeops bolometers are grouped in four frequency bands at 143 GHz (8 bolometers), 217 GHz (8 bolometers and a blind one), 353 GHz (3 polarized bolometer pairs), 545 GHz (1 bolometer). The 143 and 217 GHz channels are dedicated to the measurement of the temperature angular power spectrum of the CMB (Benoît et al. (2003a), Tristram et al. (2005b)). The 353 and 545 GHz channels allow the monitoring of both atmospheric emission and Galactic thermal dust emission. In addition, the polarization of the diffuse Galactic dust emission has been measured for the first time using the 353 GHz polarized bolometers (Benoît et al. (2004), Ponthieu et al. 92005)).

We present here the processing of the Archeops data for the KS3 flight going from raw time ordered data to maps of the sky. The Archeops data processing was specifically designed to cope with the characteristics of the scanning strategy and has similarities with Planck-HFI data processing. Other dedicated processing techniques are described in details in Hanany et al. (2000), Lee et al. 2001, Stompor et al. 2002, Rabii et al. 2005, Ruhl et al. 2003, Masi et al. (2005), Kuo et al. 2004 to deal with the Maxima, BOOMERanG, ACBAR spider web bolometer-experiments data and with WMAP HEMT all sky survey satellite dataHinshaw et al. (2003).

This paper is organized as follows. Sections 2 and 3 describe the instrumental set-up and the in-flight performances of Archeops during the KS3 flight. Section 4 presents the preprocessing of the Archeops data. In section 5 we describe the offline pointing reconstruction. Section 6 deals with the optical and time responses of the instrument. Sections 7 and 8 present the characterization and treatment of systematics and noise in the data. In section 9 we discuss the intercalibration and absolute calibration of the Archeops data. Finally, section 10 presents the construction of the Galactic and CMB Archeops maps. We conclude in section 11.

[1] http://www.archeops.org

Fig. 1. Scheme of the Archeops gondola

2. Technical description of the experiment

In this section we describe the main aspects of the instrumental setup of the Archeops experiment. Particular interest is paid to changes performed on this setup since the Trapani test flight (Benoît et al. (2002)).

2.1. Gondola

The Archeops gondola was redesigned since the Trapani flight, in order to gain some weight and try to reduce the main parasitic effect that was observed then. The most likely interpretation was indeed that stray light reflecting from or emitted by inhomogeneities on the balloon surface was the main culprit for this large scale parasitic effect. The new baffle contains lightweight highly reflective material (Fig. 1) in a staircase–like layout so that the entrance of the gondola is highly "reflective" for downward rays. To further reduce the systematics effects, between flight KS1 and KS3, the engine driving the gondola spinning was moved from the top of the gondola (and rigidly fixed to it) to an higher location along the flight chain, 60 meter above the gondola. This allowed to strongly reduce non stationary noise induced by the swivel engine.

2.2. Attitude control system

The Archeops attitude control systems are composed of gyroscopes, a GPS and a Fast Stellar Sensor. The gyroscopes are unchanged since Trapani flight. A high precision z–axis laser gyroscope based on the Sagnac effect was added for long term relative azimuth reconstruction. This is needed for daylight data, when detected stars are not enough to track rotation speed changes. The GPS was changed since Trapani because of a failure at high altitude. A 1–m diameter circular loop of copper wire was added and used as an Earth magnetic field detector to perform a rough (5 degree accuracy) absolute azimuth reconstruction. The electromagnetic influence of the pivot rotor and its associated wire on the loop signal disappeared from the KS1 to the KS3 flight, as the rotor was moved upwards along the flight chain.

The Fast Stellar Sensor (FSS) is a 40–cm optical telescope equipped with 46 photodiodes mounted on the bore–sight of the primary mirror (Fig. 1) for a–posteriori accurate pointing reconstruction. The photodiodes are aligned along a line which is perpendicular to the scanning direction. Each photodiode covers a 7.6 arcminutes (parallel to the scanning direction - para scan) by 1.9 arcminutes (perpendicular to the scanning direction - cross scan) area on the sky. The FSS sweeps a 1.4 degree wide ring at constant elevation during a payload revolution and its center is mechanically within one degree of

Fig. 2. Optical layout of the Archeops focal plane.

Fig. 3. Spectral transmission of the various types of photometric pixels. This was obtained by combining different measurements at the component level.

Fig. 4. From top to bottom, evolution of the temperature of the focal plane and of the 1.6 K and 10 K cryogenic stages during the KS3 flight

the main submillimetre telescope pointing direction. The FSS has been improved with respect to the Trapani configuration (Benoît et al. (2002)): a red filter has significantly diminished the background and parasitic noises have been suppressed. A full report on the FSS is given by Nati *et al.* (2003). During the flights, about 100 to 200 stars per revolution were detected by the FSS. A detailed description of the pointing reconstruction can be found in Sect. 5.

2.3. Detectors

For the last KS3 flight campaign, the detection was ensured by an array of 21 spider web bolometers (Bock et al. (1996)) of the same type as for the Maxima (100 mK) and BOOMERanG (300 mK) experiments. For each bolometer, a Neutron Transmutation Doped Germanium thermistor is fixed on a silicon nitride micromesh designed to absorb submillimetre light. The bolometers are cooled down below 100 mK by an ^{3}He/^{4}He dilution cryostat (Benoît & Pujol (1994)) and were optimized for the expected background loads at this temperature, varying from 2 to 8 pW depending on frequency. The bolometers were built at JPL/Caltech in the context of the development of the Planck HFI instrument (Lamarre, J.M. et al. (2003)).

Bolometer characteristics were measured from standard I–V curves obtained during ground–based calibrations at zero power load, after the bolometers were made blind (see section 3.2.2). In order to prevent radio frequencies contaminations, each bolometer is kept in a copper $\lambda/4$ cavity acting as a Faraday cage for maximal absorption.

The sensitivity of the bolometers at 100 mK is limited by the photon noise and their short time response ranges from 5 to 14 ms, which is adequate for the Archeops scanning and acquisition strategies.

2.4. Optical configuration

The Archeops optical configuration consists of a 1.5 m off-axis Gregorian telescope illuminating a set of back-to-back horns which are coupled to each of the detectors in the focal plane. The horns, which are corrugated and flared, are cooled down to 10 K by helium vapors and their wave guide sections act as frequency high-pass filters. Low-pass filters are located at the back of the horns on the 1.6 K stage. These two sets of filters define the frequency band of operation of Archeops from 100 to 600 GHz. The complete set of bolometer, filters and horn constitute a photometric pixel. Those are layed out on constant elevation (scan) lines. The telescope images these lines into curved lines on the focal plane. Figure 2 shows the focal plane layout of the photometric pixels. The layout of bolometers at different frequencies was chosen so as to have redundancies on different angular and time scales. The main axis of each photometric pixel is pointed at the image of the primary mirror through the secondary mirror. Entrances of the 10 K back–to–back horns are located above the focal plane at various heights (typically about 6 mm), in order to prevent optical cross–talks between channels.

2.5. Observation frequency bands

The Archeops data are acquired at four frequency bands centered at 143 (8 photometers), 217 (8 photometers), 353 (6 photometers) and 545 (1 photometer) GHz. The first two were dedicated to the measurement of the angular power spectrum of the CMB temperature anisotropies. The last two were designed to measure the dust diffuse Galactic emission. Figure 3 shows the spectral transmission of the various type of photometric pixels corresponding to the four Archeops frequency bands.

The 353 GHz photometers are arranged in pairs coupled to the same horn via an Ortho Mode Transducer (OMT, Chattopadhyay et al. (1999)) and are optimized to measure the polarized sky signal as described in Benoît et al. (2004).

2.6. Cryostat monitoring

Thermometers are used to monitor the cryostat temperature at each of the thermal stages described above. The thermometers, made of large thin films of NbSi, are added to the 100 mK, 1.6 and 10 K stages. They are described in Camus et al. (2000). The house keeping data obtained from these thermometers are essential for the subtraction of low frequency drifts in the Archeops bolometer data as described in Sect. 7.

3. In-flight performance

We discuss in this section the performance of the Archeops instrument during the KS3 flight in terms of cryogenics and photometry. The flight took place on February 7th 2002 and lasted 21.5 hours, starting at 12h44 UT time. During 19 hours the balloon was at nominal altitude, between 32.5 and 34.5 km above sea level, with a total of 12.5 hours of night data used for scientific purposes.

3.1. Cryogenic performance

The cryostat functioned autonomously during the entire flight duration. The dilution flow was changed twice. First it was decreased at the beginning of the mission to increase the life time

of the dilution. Then, it was increased at sunrise to compensate for the extra thermal power from the sun.

The full cryogenic system warmed up mechanically at launch, being at nominal temperature at about 15h00 UT time. Fig. 3 shows the temperature of the focal plane, the 1.6 K and the 10 K stages from top to bottom respectively. At float altitude, the focal plane cooled down staying below 100 mK during the entire flight. A plateau of about 90 mK was reached since 19h00 UT. The 1.6 K stage was stable during the entire flight at a temperature of about 1.5 K. The 10 K stage remained at about 9 K until sunrise at 27h00 UT[2], and then increased up to about 12 K. During the night flight the temperature of the bolometer bath was stable at 90 mK.

3.2. Bolometer signal and noise contributions

3.2.1. A simple photometric model

In order to evaluate *a priori* the total background incoming onto each bolometer, we performed a component by component photometric analysis by dealing with emission processes and various transmission coefficients. From the sky to the detector, it includes

- the CMB emission assuming a simple 2.725 K blackbody (Mather et al. (1999))
- the atmospheric emission for which the emissivity was computed for 41 deg. elevation (airmass of 1.52) at 32 km altitude using the Pardo's atmospheric model (Pardo *et al.* , (2002)). A temperature of 250 K is assumed.
- the radiation from the telescope which is assumed to have an emissivity of $0.00285 \times 2 \times \sqrt{1\,\mathrm{mm}/\lambda}$ (Bock et al. (1995)). The factor 2 is to account for the primary and secondary mirrors. A temperature of 250 K is assumed.
- the emission of the polypropylene window, which allows the radiation to propagate to the cold optics while maintaining the vacuum, is neglected here.
- the radiation from the 10 K stage which was found to emit in the KS1 flight a detectable fraction of the background but which was negligible for the KS3 flight. We also account for a transmission factor across the 10K stage estimated to be 0.6.
- the transmission curves shown in Fig. 3. They mostly represents the filtering done at the 1.6 K stage, although some filters were sometimes placed on the 10 K stage and a band-pass filter at the entrance of the 100 mK horn.
- the bolometer with an assumed perfect absorption.

3.2.2. A simple bolometer model

The theory of the thermodynamical and electrical behavior of bolometers is described in details by Mather (1984) and Piat *et al.* (2001). Here we concentrate on the main equations to introduce the parameterization given in subsequent tables.

[2] Meaning 3h00 UT the next day

We characterize the thermistor behavior of thermometers and bolometers using

$$R = R_\infty \exp\left(\frac{T_r}{T_1}\right)^\alpha \; . \qquad (1)$$

The electron–photon decoupling is neglected as well as electric field effects in the bolometer. The absolute temperature T_1 of the thermistor is calibrated with carbon resistance and is valid within 3 milliKelvin.

The heat equilibrium for the bolometer reads:

$$P_C(T_1, T_0) = g\left[\left(\frac{T_1}{T_{100}}\right)^\beta - \left(\frac{T_0}{T_{100}}\right)^\beta\right] = P_J + P_R \, , \qquad (2)$$

where T_0 is the base plate temperature measured by the standard thermometer, T_1 is the bolometer temperature obtained through $R(T_1)$ (Eq. 1), T_{100} is a reference temperature (we take it as $T_{100} = 100\,\mathrm{mK}$) so that the constant g is in unit of pW, P_C is the cooling power, $P_J = UI$ is the Joule power dissipated in the thermistor and P_R is the absorbed part of the incident radiative power.

Bolometer	$R_\infty(\Omega)$	T_r(K)	G(pW/K)	β	C(pJ/K)
143K01	11.27	21.16	57.96	2.80	0.40
143K03	44.23	16.60	70.62	2.30	0.42
143K04	52.91	16.85	63.83	2.30	0.47
143K05	53.41	16.85	50.94	2.30	0.35
143K07	21.55	18.79	60.30	2.55	0.38
143T01	21.47	20.03	116.29	2.85	0.57
217K01	299.42	16.73	28.93	2.10	0.18
217K02	189.54	13.21	65.15	2.00	0.36
217K03	242.93	13.10	62.87	2.00	0.03
217K04	159.03	13.76	69.45	2.20	0.39
217K05	1172.80	9.72	59.31	1.65	0.34
217K06	120.92	14.18	65.11	2.10	0.46
217T04	52.38	14.79	161.00	2.30	1.06
217T06	136.69	13.67	182.16	2.30	0.00
353K01	99.45	14.39	90.50	2.20	0.21
353K02	94.59	15.01	98.47	2.20	0.12
353K03	85.27	14.86	99.09	2.20	0.22
353K04	68.05	15.18	106.59	2.20	0.23
353K05	77.21	14.67	103.89	2.20	0.39
353K06	50.70	18.49	116.00	2.20	0.38
545K01	34.94	18.48	136.70	2.20	0.04

Table 1. Bolometer model parameters as described in Eq. 1 and 2 for each of the Archeops bolometers.

Table 1 lists the parameters of all thermometers and bolometers that were used during KS3 flight (bolometers ordered by channel, 217K05 was blind during the flight). The differential conductivity at 100 mK is $G = dP_C/dT = \beta g/T_{100}$ (from Eq. 2). These constants are consistent with those measured on cosmic rays. A more detailed description of the previous issues is given in Sect. 6. The heat capacity was simply taken as $C = \tau_1 G$ where τ_1 is the first time constant of the bolometer. Time constants are derived from a fit on Jupiter data taken during the flight, including electronic filtering and a Gaussian beam (see Sect. 6.1).

The differential conductivity G is taken at 100mK. Note that the "Kiruna" bolometers have typical conductivity between 60 and 80 pW/K and heat capacity of 0.3 to 1 pJ/K although some of them deviate significantly from this range.

3.3. Detector noise

We include in the detector noise model contributions from the FET electronics, the Johnson noise and the bolometer thermodynamic noise (Mather (1984)). To the detector noise we add quadratically the photon noise deduced from our photometric model. Note that the bolometer noise is not white at high frequency due to the bolometer time response. Figure 5 shows an example of power spectra of the time ordered data of four representative Archeops bolometers during the KS3 flight. We overplot the noise model discussed above which is in qualitative agreement without any parameter tuning at frequencies higher than a few Hz. We observe an increase of power with decreasing frequency mainly due to the low frequency systematics. Although we have smoothed out the power spectrum we still can observe peaks which correspond to the sky signal at the spin frequency harmonics which are mainly dominated by Galactic and atmospheric emissions. Centered at 1 Hz and in particular for the high frequency channels there is a very peculiar structure which may be of atmospheric origin. Finally at high frequency we observe correlated structures. A more detailed description of systematics and their subtraction is given in Sect. 7.

Finally, we present in table 2 a summary of the noise properties of all Archeops bolometers. From left to right we include representative values within the night flight for the main photometric quantities of those bolometers: current, resistance, and responsivity. Next we provide the expected absorbed power from a simple photometric model made of subsystem transmission measurements presented in section 3.2.1. Then we give the absorbed power as measured (with 1 pW absolute uncertainty) using the bolometer model described in section 3.2.2. The efficiency is given as the ratio of Jupiter inflight calibration with calibration from the photometric model. Noise measurements are given at the bolometer level both for photon and total noise. The photon noise is within a factor 2 of the total noise as measured in flight conditions.

4. Preprocessing

In this section, we describe the preprocessing of the Archeops data. This includes the demodulation of the raw data and the removal of the parasitic signal introduced by the readout electronic noise. We also describe the linearity correction of the bolometers and the flagging of the data affected by cosmic rays and noise bursts.

4.1. Prefiltering

The data are acquired in total power mode via an AC square wave modulated bias. All the modulations are driven by the same clock at 76.3 Hz, leading to an acquisition frequency

Fig. 6. Top : Kernel of the digital filter used for demodulation (see text for details). Bottom : Fourier power spectrum of the digital filter compared to a square filter, to the beam pattern and to the bolometer time constant.

f_{acq} = 152.6 Hz. The AC square wave modulated bias transforms the data into a series of alternative positive and negative values. This induces a peak at the Nyquist frequency, $f_{acq}/2$, in the Fourier power spectrum of the bolometer data. This peak fully dominates the signal and needs to be removed for demodulation. This is performed by filtering the data and for this purpose we have constructed a digital filter with the following constraints:

- the transition after the cut-off frequency, taken to be 60 Hz, must be sharp for a complete removal of the modulation signal,
- the ringing of the Fourier representation of the filter above the cut-off frequency needs to be below the 2% level, to avoid any possible aliasing.

These two constraints lead to a digital filter of 23 points whose kernel is shown on the top panel of Fig. 4.1. The Fourier response of the filter is shown on the bottom panel and compared to that of a simple square filter. We observe that the high frequency cutting of the digital filter is much sharper than for the square filter therefore preserving the signal better. For comparison, we also plot the Fourier response of the bolometer time response and of the beam pattern which determine the spectral band for the signal. No signal is therefore removed by the digital filter.

4.2. Removal of readout digital noise

As discussed above, the bolometer signal is biased with a square signal. The data are then amplified by a digital preamplifier and buffered and compressed by the on-board computer into blocks. The blocks are then recorded. The compression procedure preserves most of the signal of interest. Code 32-bit words at the beginning and end of each block allows us to check those blocks. These blocks are of different sizes depending on the nature of data which may correspond to the signal from the gyroscopes, the bolometers, the thermometers or the stellar sensor. The length of the bolometric and thermometric blocks is of 72 samples.

Fig. 7. Top: Fourier power spectrum of KS3 143K01 bolometer data showing the frequency peaks produced by the readout electronic noise. Bottom: Same after preprocessing. The amplitude of the peaks is significantly reduced.

While the on-board computer deals with in-flight commands, the data recording is delayed and a few data blocks

Fig. 5. From top to bottom and from left to right are shown the power spectra (in $10^{-17}\,\mathrm{W.Hz}^{-\frac{1}{2}}$) of the Archeops 143K03, 217K06, 353K01 and 545K01 bolometers, respectively, as a function of frequency (in Hz). For comparison we overplot (smooth curve) the detector noise contribution for each bolometer as given by the model presented in the text.

Bolometer	I (nA)	R (Ω)	Resp (10^8 V/W)	P_{exp} (pW)	P_{abs} (pW)	Eff	NEPphot ($10^{-17}\,\mathrm{W.Hz}^{-1/2}$)	NEPtot ($10^{-17}\,\mathrm{W.Hz}^{-1/2}$)
143K01	0.57	2.78	4.98	1.7	2.6	1.3	2.2	5.1
143K03	0.57	2.76	4.49	1.7	2.9	1.8	2.4	3.6
143K04	0.57	4.11	6.65	1.7	1.8	0.7	1.9	3.0
143K05	0.57	2.33	4.27	1.7	2.9	1.7	2.4	5.1
143K07	0.57	2.04	3.51	1.7	3.4	1.6	2.5	6.7
143T01	1.13	3.90	4.57	1.3	1.9	1.3	1.9	4.4
217K01	1.70	0.95	2.04	2.0	6.1	1.3	4.2	9.1
217K02	1.70	0.64	1.31	2.0	8.6	2.0	5.0	9.4
217K03	1.70	1.08	2.22	2.0	5.2	0.2	3.9	7.3
217K04	1.22	1.11	1.93	3.5	6.7	1.8	4.4	9.5
217K05	1.70	0.89	1.64	2.0	7.7	1.0	4.7	7.4
217K06	1.13	0.98	1.86	3.5	6.3	1.7	4.3	8.1
217T04	0.91	4.39	5.29	2.1	0.5	0.7	1.2	4.4
217T06	0.87	5.05	4.65	2.1	2.8	1.2	2.8	6.4
353K01	0.85	3.31	5.00	1.1	2.0	0.7	4.3	3.8
353K02	0.85	3.98	5.37	1.1	1.9	0.6	4.2	3.8
353K03	0.85	3.75	5.30	1.1	1.7	0.6	4.0	3.4
353K04	0.85	3.82	5.36	1.1	1.6	0.7	3.8	4.8
353K05	0.85	3.42	4.99	1.1	1.9	0.7	4.2	3.7
353K06	0.85	5.16	5.56	1.1	3.0	0.6	5.3	4.9
545K01	1.13	0.77	0.76	7.5	18.0	1.2	11.4	15.9

Table 2. For all Archeops bolometers from left to right. Photometric quantities as representative of night flight values: the current, the resistance, and the responsivity. Expected absorbed power from a simple photometric model made of subsystem transmission measurements presented in section 3.2.1. Absorbed power as measured (with 1 pW absolute uncertainty) with the bolometer model described in section 3.2.2. Efficiency as the ratio of Jupiter inflight calibration with calibration from the photometric model. Photon and total noise.

are buffered before recording. Small offset variations in the electronics lead to significant differences between the mean value of the last recorded blocks and the next ones. As in-flight commands are sent and received by the on-board computer periodically during the flight (every few data blocks), the differences in the mean between blocks induce a parasitic signal on the data. This parasitic signal shows up in the data as a periodic pattern of basic frequency $f_{acq}/72$. Further, as series of blocks are buffered before recording we also observe in the data periodic patterns at frequencies which are submultiples of $f_{acq}/72$. For most of the bolometers this systematic signal dominates over the noise and is clearly visible both in the time and frequency domain. The top panel of Fig. 7 shows a zoom-up of the power spectrum of the data of the KS3 143K01 Archeops bolometer. We observe on the spectrum a series of peaks which correspond to the parasitic signal.

The subtraction of the parasitic periodic signal can be easily achieved using a time domain template for it. Indeed, we have implemented a fast algorithm for calculating a time varying template of the parasitic signal. First of all, for each Archeops timeline we have divided the data into pieces of N blocks of 720 samples. The block size corresponds to the largest period between two in-flight commands. Then each piece of data has been reordered into a $720\times N$ matrix so that a time evolving pattern of the parasitic signal over 720 samples can be calculated by smoothing up over the N blocks. The exact number of 720-samples blocks to be summed up is a compromise between, first, the minimum signal to noise ratio needed for extracting the parasitic signal from the data; second, the time evolution rate of the parasitic signal and third, the minimum time interval needed to consider that the sky signal varies sufficiently for not contributing to the template. We have found that for most Archeops bolometers $N = 100$ is a good compromise. The constructed template is repeated N times (size in samples of the time interval processed) and then subtracted from each piece of data.

The bottom panel of Fig. 7 shows the power spectrum of the KS3 143K01 bolometer after applying the above procedure. The procedure reduces significantly the peaks. For example the fundamental frequency peak at 2.12 Hz is reduced to much less than 10 % of its original value. The peak at 12.7 Hz, although significantly reduced, is still visible in the preprocessed spectrum. It will be cut off in the Fourier domain as discussed in Sect. 7.3.

4.3. Linearity correction

The cryostat temperature underwent a slow decrease during the flight, leading to a slow change of the calibration in mK/μV. This change in calibration can be corrected for by modeling the responsivity of the bolometer. Actually, for a TOI b in μV, we can write the linearity corrected TOI as follows

$$b_{corr} = -V_b \ln \frac{V_b + V_0 - b}{V_b} + V_0 \tag{3}$$

The parameters V_b and V_0 are determined from the bias-current curves of each of the bolometers. After this smooth correction, the calibration factor in mK/μV can be considered as constant over the flight, thus allowing for a much easier determination. For the KS3 flight the correction does not exceed 20 %, and it is only important for the first 2 hours of flight. This has been cross-checked via the Galactic plane calibration method described in Sect. 9.2.

4.4. Flagging of the data

In this section, we describe the identification and flagging of parasitic effects including glitches, noise bursts and jumps in the data. For Archeops most glitches are due to the increase of temperature of the bolometer due to the energy deposited by cosmic rays hits. Jumps are essentially due to changes of the equilibrium voltage of the bolometer and there are only a few during the whole flight. Bursts of noise are induced by microphonic noise coming mainly from the mechanical oscillations of the gondola.

To flag and remove the data affected by the above systematic effects, the first step is to detect spikes in the TOIs above a certain threshold level. For this purpose the r.m.s. noise level, σ^2, is estimated locally on a 400 points running window as the standard deviation from the median value, m, of the data after removing 5% of the lowest and largest data values. The data with flux above 8σ are considered as glitches. To preserve the Galactic signal, which can be sometimes spiky or/and larger than the threshold limit, a baseline f_{base} fitted as a combination of the two first Fourier modes is removed whenever data values above the threshold are detected at Galactic latitude between -10^{o} and +10^{o}. The value of σ is then re-computed and the above criteria re-applied. This technique is time-consuming but not required outside of the Galactic plane where a flat baseline is already a very good approximation.

The second step is then the flagging of the data. When the parasitic signal is due to a glitch, we can model it by the convolution of a Dirac delta function at time t_i with the sampling window and a double decreasing exponential function with two time constants τ_{short} and τ_{long}. The first corresponds to the relaxation time of the bolometer itself and the second is of unknown origin. The time constant values depend only on the bolometer and must be the same for all glitches impacting this bolometer. The main objective of this first analysis is not to reproduce faithfully the glitch shape but to estimate which part of the data is badly affected by it and must be flagged. Therefore, the same conservative values are adopted for all bolometers, τ_{short} = 2 samples (13 ms) and τ_{long} = 50 samples (325 ms). We then fit the following glitch model

$$f(t,t_i) = \left[A_{short}\, e^{-\frac{t-t_i}{\tau_{short}}} + A_{long}\, e^{-\frac{t-t_i}{\tau_{long}}}\right] * f_{acq} \quad + \quad f_{base} \tag{4}$$

where the free parameters are the amplitudes of exponential functions A_{short} and A_{long} and the baseline and where f_{acq} is the sampling frequency. All data samples within t_{min} and t_{max} given by

$$\begin{aligned} t_{min} &= t_i - 11 \\ t_{max} &= t_i + \tau_{short} \ln\left[\frac{A_{short}}{0.1\sigma}\right] + \tau_{long} \ln\left[\frac{A_{long}}{0.1\sigma}\right] + 11 \end{aligned}$$

are flagged. So data samples for which the glitch contribution is at a level higher than 10 % of the local noise are flagged. The extra 11 samples margin on each side of the glitch position accounts for the effect of the digital filter at 23 points discussed in the previous subsection. An additional margin of 100 samples is used when the fits is of poor quality. This extra flagging concerns about 20 % of the glitches detected on the OMT bolometers, 33 % on the Trapani-like bolometers and less than 15 % for the others bolometers of the KS3 flight.

Detailed statistics of the number of glitches detected in the KS3 flight are reported in Tab. 3. The bolometers from the Trapani flight are quite sensitives to glitches, 15 to 20 glitches per min. Polarized OMT at 353 GHz shows a rate of ~4 glitches per minute, whereas at 217 GHz and 545 GHz we detect less than 2 glitches per minute. At 143 GHz the bolometers present a glitch rate between 1.5 and 4 per minute. The glitch rate is fully related to the effective surface of the bolometer which varies between bolometers. A larger glitch rate can be explained by a larger effective area of the spider-web absorber.

In the above procedure bursts of noise on the data are assimilated to glitches and the flagging obtained is poor. To ensure a better flagging, we proceed to a visual inspection of the data. We check all the pieces of data found above the threshold limit and extend manually the flagging if necessary. Those data samples affected by noise bursts are flagged as such. We also observe jumps on the data which are caused by extreme changes on the DAC currents of the bolometer.

The values of the DAC currents are stored as housekeeping data and allows us to correct the data from those jumps via a simple destriping algorithm. In addition, by visual inspection we determine the data samples which are affected by jumps and they are manually flagged.

At the end of the process, a total of 1-2.5 % (resp. 2-4 % and 12-18 %) of the data are flagged for the KS3-like bolometers (resp. for the OMT and Trapani-like bolometers). Flagged data are then replaced by constrained realization of noise as discussed in Subsect. 8.4.

5. Pointing reconstruction

The knowledge of the pointing attitude was not needed during the flight but its accurate *a posteriori* reconstruction is critical

Bolometer	# glitches [per min.]	data flagged [%]
143K01	1.8	0.93
143K03	3.6	1.58
143K04	4.2	1.74
143K07	1.6	0.77
143K05	2.2	0.94
143T01	16.8	8.58
217K01	1.0	0.44
217K02	1.1	0.54
217K03	1.3	0.55
217K04	1.6	0.79
217K05	1.3	0.58
217K06	1.5	0.79
217T04	16.9	8.43
217T06	20.7	11.62
353K01	4.8	2.15
353K02	4.1	1.88
353K03	5.7	2.55
353K04	3.8	1.72
353K05	4.9	2.22
353K06	3.3	1.52
545K01	1.1	0.76

Table 3. Statistics of glitches per minute for the KS3 flight and proportion of flagged data.

for mapping correctly the sky signal. The pointing of each of the detectors in the focal plane is computed as follows. First, a pointing solution for the payload is obtained from the processing of optical data collected by the fast stellar sensor (FSS) during the flight. Finally, we estimate the pointing offset with respect to the payload axis for each bolometer using the reconstruction of the focal plane from measurements of point sources (see Sect. 6 for details).

We have developed an algorithm to extract star candidates from the FSS time-sampled photodiode signals (see Sect. 2.2). Each star candidate is kept into a table including its detection time, its position along the diode array and the electrical intensity observed. The position of the star candidate along the diode array is given in terms of an effective diode number. The electrical intensity measured is proportional to the logarithmic value of the flux of the star.

5.1. Coordinate system definition

In the following, we use equatorial coordinates $\{\alpha, \delta\}$ to define the position of celestial objects on the sky. The FSS data are also easily handled with local coordinates associated with the gondola frame, for which the zenith corresponds to the gondola spin axis direction. The direction of a star on the celestial sphere is then given by θ, the angular distance between the spin axis and the direction of the star (hereafter the axial distance), and by φ, the phase corresponding to the azimuth measured from the North.

To reconstruct the pointing direction of the gondola we need to find the direction of the center of the diode array. The instantaneous pointing solution is fully described by the set $\{\alpha_p, \delta_p, \varphi\}$, where α_p and δ_p are the equatorial coordinates of the gondola spin axis and φ, the phase for the diode array. Note that the phase value φ is the same for all the diodes in the array, therefore also the same for all detected stars, because the diode array is placed perpendicularly to the scanning direction. In other words, the number of the diode lightens is only given by the axial distance of the observed star.

5.2. Reconstruction Method

The goal is to produce an optimal pointing solution as a function of time. The reconstruction is based upon the comparison between FSS data and a dedicated star catalog compiled from the Hipparcos catalog. The electrical intensity of stars in the catalog is computed by taking into account the FSS spectral response. Hereafter, we call *signal* a star candidate in the list produced by the FSS software and *star* an object taken from the star catalog. First of all, we find in the star catalog the best star to be associated which each FSS signal. We call identified signal a signal for which this association is performed. Via these associations we obtain a pointing solution for each identified signal. Finally, we fit the overall set of identified signals through the scan path to get a pointing solution as a function of time.

5.3. Initial pointing estimate

To be able to associate signals to stars, a first estimate of the pointing solution is needed. This is obtained via the GPS data which give the local vertical direction, which corresponds to the spin axis direction $\{\alpha_p, \delta_p\}$ to an accuracy of $\sim$ 1 degree, taking into account the gondola average pendulation. Then, we match signal and star directions and try to identify for each signal the corresponding star. There is no direct measurement of the FSS phase φ. We need to reconstruct it from the rotation period by integration.

5.3.1. Rotation period

We now describe the gondola motion relative to the celestial sphere. We thus call rotation period the elapsed time between two successive detections of the same star after one revolution. Each revolution takes about 30 seconds. Due to the Earth motion, the spin axis moves about 5' in α per revolution. Each star can thus be seen several times by the FSS. For each signal, we look for every compatible signal seen in the preceding revolution. A compatible signal has a similar intensity and a nearby diode number. Time differences between the signal and those seen in the last revolution are binned into an histogram. The most populated bin gives us the rotation period. Figure 8 shows the evolution of the rotation period as a function of time for 3 hours of the KS3 flight. This evolution is mainly due to the presence of strong stratospheric winds during the flight.

Fig. 8. *Rotation period evolution during the KS3 flight.*

5.3.2. Star Sensor Phase

We reconstruct the FSS phase by integrating the angular speed $\frac{1}{T}$, where T is the rotation period. The resulting estimate $\hat{\varphi}$ differs from the phase by a slowly varying offset. To correct from this bias, we compare, for each revolution, the phase of the most intense signals with the phase of the brightest stars located in the 1.4 degree wide band scanned by the diode array during a revolution.

Fig. 9. *Evolution of the distribution of phase differences between signals and bright stars for the KS3 flight.*

Fig. 10. *Distribution of the axial distance of bright stars versus the diode number of the corresponding intense signals. Notice the strange behavior of the diode 26. This diode is excluded from analysis.*

The analysis of phase differences $\varphi^{\star}$-$\hat{\varphi}$ gives us the FSS phase offset shown in Fig. 9. The distribution of axial distance, θ, values of bright stars associated to intense signals allows us to adjust the geometrical relation between the axial distance and the diode coordinates along the array. Figure 10 shows the distribution of the axial distance of bright stars as a function of the diode number of the corresponding intense signal in the FSS. We observe for each diode number the distribution has a well defined peak from which we can reconstruct the axial distance for each diode. The width of the peak is due to the pendulation motion of the gondola.

5.4. Star-signal matching algorithm

The association algorithm used above is based on a comparison of the star and signal directions. An error $\boldsymbol{\delta}$ on the spin axis direction (α_p, δ_p) translates into a local rotation and then an error on the reconstructed direction for each of the signals. The gondola pendulation is a slow time varying function on scales of a few degrees. Therefore, the error $\boldsymbol{\delta}$ and the local rotation parameters, are slowly varying functions too. In other words, signals detected within a few degrees area are thus shifted a roughly equal amount from their true position on the celestial sphere.

The matching algorithm is based on the above statement and proceed as follows. First, for each signal, we associate stars and signals with compatible positions and intensities. Second, given a reference signal, we check whether for the N following signals there are N stars such that the corresponding shifts are close. If so, this displacement is the signature of a local rotation induced by a wrong reconstruction of the spin axis direction or by a wrong estimate of the FSS phase.

Free parameters like the number N of signals used or the tolerance on the angular distance between the signal and its corresponding star directions can be tuned to optimize the association efficiency. In practice, tight cuts on those parameters reduce the probability of wrong associations but at the same time reduce the number of good associations available on the regions where the pointing reconstruction is bad. To improve this situation we use the fact that the FSS sees a given star during several revolutions. Once a good association is obtained we propagate this information to the whole data set using our estimate of the rotation period and thus we can improve the association efficiency and therefore the pointing solution.

5.5. Pointing solution improvement

The axial distance θ is the only quantity which can be directly measured. When signals have been associated to catalog stars, it gives a way to reconstruct the spin axis direction. As the position of the signal and that of its associated star must be the same, the spin axis is therefore located on a cone centered on the star with an opening angle θ. Using two couples, signal-star, we can find the direction of the spin axis. Indeed the intersection of the two cones, one for each couple, leads to two solutions. Only one of them is geometrically relevant. Using the whole data set we can thus correct the estimate of the spin axis direction during the flight. We upgrade the FSS phase taking into account the new estimate of the spin axis pointing. The process is iterative to obtain a more accurate estimate of the pointing for the whole flight. The increase in accuracy at each iteration allows us to use tighter cuts to get a better quality matching between stars and signals.

The FSS dataset available is mainly composed of faint stars making the above iterative solution very important. Further, calibration uncertainties on the signal get broader as the intensity decreases. The associations for the brightest stars allows us to recalibrate the FSS signals. Adding finer constraints on the intensity of the signal increases the quality of its association to a star in the catalog. This also improves the final pointing solution.

5.6. Scan path fit

Once the signal-star associations are obtained we have a discrete pointing solution at the times where the signal were observed. Our purpose is to generate an optimal continuous scan path and then we have to interpolate the pointing solution along FSS data. This solution should not only be interpolated, but also optimized along the data set $\{x_i, t_i\}$. To get an optimal pointing solution we have to reconstruct ($\tilde{\alpha}_p(t)$, $\tilde{\delta}_p(t)$, $\tilde{\varphi}(t)$), from the $\{\alpha_{p\,i},\ \delta_{p\,i},\ \varphi_i\}_i$ set, where i labels a given signal-star association. This is performed by computing first a smooth solution for the pointing and then correcting it.

Smooth pointing solution

We first produce a smooth solution for the pointing ($\tilde{\alpha}^0_p$, $\tilde{\delta}^0_p$ and $\tilde{\varphi}^0$) by fitting the set $\{\alpha_{p\,i},\ \delta_{p\,i},\ \varphi_i\}_i$ using a chi-square minimization. As the set $\{\alpha_{p\,i},\ \delta_{p\,i},\ \varphi_i\}_i$ is irregularly sampled in

time we obtain a generic interpolation, $\tilde{x}(t)$, of the pointing solution through a decomposition of the form

$$\tilde{x}(t) = \sum_k c_k U(t - \hat{t}_k) \tag{5}$$

where each $U(t - \hat{t}_k)$ is a generic kernel of the form $sinc(\frac{\pi t}{p})e^{-\frac{t^2}{2p^2\sigma^2}}$ centered at $t = \hat{t}_k$. We choose the parameter p to optimize the representation of the low frequency components in $\tilde{x}(t)$ and σ.

The coefficients $\{c_k\}$ are obtained from the minimization of the chi-square

$$\chi^2 = \sum_i (x_i - \tilde{x}_i)^2$$

leading to the following linear system

$$\sum_{k=1}^{N} \left(\sum_i U(t_i - \hat{t}_l) U(t_i - \hat{t}_k) \right) c_k$$

$$= \sum_i x_i U(t_i - \hat{t}_l) \qquad \text{with} \quad k, l = 1, 2, \ldots, N.$$

We solve this system for the three quantities of interest $\alpha_p(t)$, $\delta_p(t)$, and $\varphi(t)$.

Corrected pointing solution

Once we have a first smooth solution for the pointing ($\tilde{\alpha}_p^0$,$\tilde{\delta}_p^0$ and $\tilde{\varphi}^0$) we compute corrections to it $\Delta\tilde{\alpha}_p(t)$, $\Delta\tilde{\delta}_p(t)$ and $\Delta\tilde{\varphi}(t)$. For this purpose we decompose these 3 quantities in terms of kernel functions as in Eq. 5. We call Δa_k, Δd_k and Δp_k the decomposition coefficients for $\Delta\tilde{\alpha}_p(t)$, $\Delta\tilde{\delta}_p(t)$ and $\Delta\tilde{\varphi}(t)$ respectively. In this case we consider high frequency terms to optimize the pointing solution.

The FSS dataset $\{\alpha_{p\,i},\ \delta_{p\,i},\ \varphi_i\}_i$ can be rewritten more explicitly as $\{\alpha_{p\,i}, \delta_{p\,i}, \varphi_i, \theta_i, \alpha_i^\star, \delta_i^\star\}_i$. θ_i is a linear function of the diode number. $\alpha_i^\star$ and $\delta_i^\star$ are the coordinates of the star corresponding to signal i. This set can also be expressed for the star position in gondola frame coordinates $\{\alpha_{p\,i}, \delta_{p\,i}, \varphi_i, \theta_i, \varphi_i^\star, \theta_i^\star\}_i$. We can obtain an estimate of the pointing corrections by comparing the reconstructed star positions with the pointing position at the time of their observation.

$$\chi^2 = \sum_i \left\{ \left(\frac{\varphi_i^\star - \tilde{\varphi}_i}{\sigma_i^\varphi} \right)^2 + \left(\frac{\theta_i^\star - \theta_i}{\sigma_i^\theta} \right)^2 \right\} \tag{6}$$

We note σ_i^θ and σ_i^φ the errors associated with the measurements of θ and φ obtained in the previous section. There are two sources of asymmetry between σ_i^θ and σ_i^φ. The axial distance coordinate θ is directly measured by the FSS. The phase coordinate must be reconstructed, once the spin axis direction is known. The second source is geometric. A diode covers 1.9 arcminutes in the cross-scan direction by 7.6 arcminutes along the scan. We use $\sigma_i^\theta = \sigma$ and $\sigma_i^\varphi = 2\sigma$.

The star coordinates $\varphi^\star$ and $\theta^\star$ in the gondola frame depend on the spin axis direction. A variation $\Delta\tilde{\alpha}_p$ and $\Delta\tilde{\delta}_p$ in this direction induces a modification of the coordinates $\theta^\star$ and $\varphi^\star$. To first order, we have

$$\begin{cases} \theta^\star = \theta^{\star\,o} + c_{11}\Delta\tilde{\alpha}_p + c_{12}\Delta\tilde{\delta}_p \\ \varphi^\star = \varphi^{\star\,o} + c_{21}\Delta\tilde{\alpha}_p + c_{22}\Delta\tilde{\delta}_p. \end{cases}$$

The coefficients c_{ij} are known functions of $\alpha_p{}^o$, $\delta_p{}^o$, $\theta^{\star\,o}$ and $\varphi^{\star\,o}$.

Then Eq. 6 becomes

$$\chi^2 = \sum_i \left(\frac{\varphi_i^{\star\,o} - \tilde{\varphi}_i^o + c_{21}\Delta\tilde{\alpha}_p + c_{22}\Delta\tilde{\delta}_p - \Delta\tilde{\varphi}}{\sigma_i^\varphi} \right)^2 + \left(\frac{\theta_i^{\star\,o} - \theta_i + c_{11}\Delta\tilde{\alpha}_p + c_{12}\Delta\tilde{\delta}_p}{\sigma_i^\theta} \right)^2.$$

To achieve convergence, we follow the same steps as the method described in 5.5. We first calculate the correction on the spin axis direction $\Delta\tilde{\alpha}_p(t)$ and $\Delta\tilde{\delta}_p(t)$. This leads us to minimize the quantity

$$\chi_1^2 = \sum_i \left(\frac{\varphi_i^{\star\,o} - \tilde{\varphi}_i^o + c_{21}\Delta\tilde{\alpha}_p + c_{22}\Delta\tilde{\delta}_p}{\sigma_i^\varphi} \right)^2 \tag{7}$$

$$+ \left(\frac{\theta_i^{\star\,o} - \theta_i + c_{11}\Delta\tilde{\alpha}_p + c_{12}\Delta\tilde{\delta}_p}{\sigma_i^\theta} \right)^2. \tag{8}$$

The phase correction is then obtained by taking

$$\chi_2^2 = \sum_i \left(\frac{\varphi_i^{\star\,o} - \tilde{\varphi}_i^o + c_{21}\Delta\tilde{\alpha}_p + c_{22}\Delta\tilde{\delta}_p - \Delta\tilde{\varphi}}{\sigma_i^\varphi} \right)^2. \tag{9}$$

The minimization of χ_2^1 and χ_2^2 leads to the iterative resolution of two linear systems with free parameters Δa_k, Δd_k and Δp_k.

In the above we have assumed that the photodiodes array was oriented perpendicularly to the pointing direction. This hypothesis can be verified by comparing the phase for the stars with the phase of the FSS as a function of the diode number. This comparison is shown on Fig. 11. We observe a phase shift which indicates that the photodiodes array is tilted along the scan direction. Given the 1.8 m focal length of the parabolic mirror and a 1mm photodiode area along cross-can direction, we find an inclination of ∼ 3 degrees. The phase of each signal is thus corrected to take this effect into account.

Fig. 11. 2D histogram showin'g a variation of phases difference between signals and associated stars with the signal diode number.

5.7. Accuracy

We have of two independent but complementary ways of assessing the accuracy of the Archeops pointing reconstruction. A first estimate can be obtained from the distribution of coordinate differences between the signals and their associated stars. Figure 12 show the distribution of errors in the plane axial distance-phase before and after scan path fit respectively. The 95% and 68% confidence level contours are displayed in white. We observe that the axial distance coordinate has intrinsically a better accuracy by a factor 2.5. Further, we notice a significant decrease of the errors for both the axial distance and the phase.

We can also estimate the errors in the pointing reconstruction via the Fisher matrix of the free parameters in the scan-path fit described by Eq.8 and 9. This gives us a continuous estimate of the pointing error which is used to flag those regions for which the pointing is badly known. Hereafter, we call this flag on the data bad pointing flag. The distribution of equatorial coordinate differences in Fig. 13 shows that the attitude reconstruction is achieved with an accuracy better than 1.5 and 1 arcmin in RA and DEC respectively, at the 1-σ level.

Fig. 12. From top to bottom, distribution of errors in axial distance - phase plane with 95% and 68% confidence levels (in white) before and after scan path fit respectively.

Fig. 13. KS3 flight 95% end 68% confidence levels for error distribution in equatorial coordinates after scan path fit.

6. Bolometer response

Fig. 14. Top: map of Jupiter for the 143K03 bolometer in μV before time constant deconvolution. The map is represented in the par and cross scan direction in arcmin. Bottom: As above but after deconvolution from the time constant.

We describe in this section the reconstruction of the Archeops focal plane parameters for the KS3 flight. For this purpose we estimate the time response of the bolometers, the optical response of the photometric pixels and the focal plane geometry on the celestial sphere. The focal plane is reconstructed using planets observations. The brightest one, Jupiter, is observed twice at ~ 16.5 and 21h00 UT hours and can be considered as a point source at the Archeops resolution (apparent diameter of 45 by 42 arcsec). We also use Saturn observations obtained at 15h36 and 18h427 UT hours to cross check the results. Saturn can be also considered as a point source at the Archeops resolution (apparent diameter of 19 by 17 arcsec).

For each detector, we start by computing local maps of the planets in azimuth-elevation coordinates which correspond to the along-scan and cross-scan directions. These maps are obtained by projecting the TOI data without filtering. To remove the zero level in these maps we estimate a baseline in the TOI which is then subtracted. The latter is estimated from a TOI where all the flagged data are interpolated using a constrained realization of noise. The TOI signal obtained for planet observations is the superposition of two main effects. First, the convolution of the source sky signal with the beam pattern of the photometric pixels. Second, the convolution of the bolometric signal with the time response of the bolometers which is characterized by a time constant. Both effect are clearly visible in the Jupiter map shown on the top panel of Fig. 14. The beam pattern convolution widens up the point source signal both in the cross-scan and along-scan directions. The effect of the time response convolution appears as a tail in the map along the scan direction.

In our analysis we first estimate the bolometer time constants for each using in-scan profiles of the Jupiter or Saturn map. Then we deconvolve the TOI from the bolometer time constant and recompute local maps as the one presented on the bottom panel of Fig. 14. From these maps, we characterize the beam pattern of the photometric pixels.

6.1. Time response

6.1.1. Optical time constants estimate

The time response, TR, of the bolometers can be described by the combination of two decreasing exponentials with time constants τ_1 and τ_2

$$TR(t) = (1-\alpha)\, e^{-t/\tau_1} + \alpha\, e^{-t/\tau_2} \qquad (10)$$

with α a mixing coefficient to be estimated from the data. As Archeops scans the sky at roughly constant speed, the effect of beam pattern and time response are degenerate in the along-scan direction. In order to have the simplest possible model, but that allows us to separate both effects, we will assume that the beam pattern shape is symmetric along the scanning direction. [3]

The time constants are estimated fitting the Jupiter profiles using a χ^2 minimization for a grid of 3 parameters τ_1, τ_2 and α which are set in the range [1,10] ms, [10,100] ms and [0,1] respectively. The profiles used are the 4 arcmin cross-scan average of local maps of the two Jupiter crossings. For each set of parameters, we deconvolve the initial TOI from the $TR(\tau_1, \tau_2, \alpha)$. We then fit a Gaussian on the rising part of the beam profile and use a Gaussian with the same amplitude and

[3] Notice that for a constant angular speed the effect of the time response convolution can be assimilated to a beam convolution.

sigma for the decreasing part. We do not account for the higher part of the beam shape that can present several maxima (especially multimode ones) by fitting only the lower 80% of the profile data.

We compute the minimum of the χ^2 in the (τ_1, τ_2), (τ_1, α) and (τ_2, α) planes. The best-fit parameter values are obtained from the average of the two maxima obtained for each parameter. By integrating the surface we obtain directly the 1σ error bars. If α is compatible with 0 within 1σ, we re-compute the estimation of τ_1 using a single time constant model to reduce the error bars.

Figure 15 shows one of the Jupiter map profile for the 217K04 bolometer before (in red) and after (in black) deconvolution from the bolometer time response. The tail in the profile due to the time response is clearly suppressed after deconvolution.

Fig. 15. 217K04 Beam profile on Jupiter before (in red) and after (in black) deconvolution of the two time constants ($\tau_1 = 5.57^{+1.01}_{-1.08}$ ms, $\alpha = 0.48^{+0.04}_{-0.04}$ and $\tau_2 = 38.38^{+3.80}_{-4.20}$ ms).

bolometer	$\tau_1(ms)$	α	$\tau_2(ms)$
143K01	$6.87^{+0.78}_{-0.83}$	$0.32^{+0.05}_{-0.06}$	$62.16^{+35.03}_{-24.23}$
143K03	$5.98^{+0.52}_{-0.58}$	0.00	-
143K04	$7.36^{+0.97}_{-0.99}$	$0.20^{+0.09}_{-0.10}$	$21.84^{+19.71}_{-11.84}$
143K05	$6.91^{+0.82}_{-0.79}$	$0.25^{+0.08}_{-0.08}$	$21.49^{+6.39}_{-5.54}$
143K07	$6.23^{+0.76}_{-0.85}$	0.00	-
143T01	$4.94^{+0.39}_{-0.40}$	0.00	-
217K01	$6.07^{+1.58}_{-1.93}$	$0.38^{+0.07}_{-0.06}$	$23.20^{+9.34}_{-6.64}$
217K02	$5.57^{+1.10}_{-1.34}$	0.00	-
217K03	$0.52^{+2.20}_{-0.52}$	0.00	-
217K04	$5.57^{+1.01}_{-1.08}$	$0.48^{+0.04}_{-0.04}$	$38.38^{+3.80}_{-4.20}$
217K05	$5.81^{+0.93}_{-0.92}$	0.00	-
217K06	$7.04^{+0.53}_{-0.55}$	0.00	-
217T04	$6.57^{+0.61}_{-0.54}$	0.00	-
217T06	$0.00^{+0.00}_{-0.00}$	0.00	-
353K01	$2.28^{+1.12}_{-1.28}$	0.00	-
353K02	$1.17^{+1.69}_{-0.17}$	0.00	-
353K03	$2.26^{+1.00}_{-1.11}$	0.00	-
353K04	$2.14^{+0.87}_{-1.05}$	0.00	-
353K05	$3.79^{+0.99}_{-1.38}$	0.00	-
353K06	$3.25^{+0.96}_{-1.19}$	0.00	-
545K01	$0.28^{+0.54}_{-0.28}$	0.00	-

Table 4. Bolometer time constants for the Archeops KS3 flight

In Tab. 4 we present, for each of the Archeops bolometers, the values of $\tau_1(ms)$, α and $\tau_2(ms)$ obtained from the analysis of the Jupiter profiles. The analysis of the Saturn profiles provides consistent results.

6.1.2. Estimate of the bolometer time constant from glitches

The time response of the bolometer can also be estimated using the signal from cosmic ray glitches with short time constant (see Sect. 4.4) which hit directly the bolometer. To a very good approximation, for these glitches, the signal is just the convolution of a Dirac delta function with the bolometer time response and the sampling kernel and therefore they have all the same shape. A template of this can be obtained by piling up all short glitches in the data after common renormalization both in position and amplitude. We can then fit to this template the glitch model (Eq. 4) to estimate τ_{short}. Notice that only a few glitches have an additional significant long time constant preventing us from reconstructing an accurate template.

Figure 16 shows in black the glitch template computed for the bolometer 217K01. In red we trace the best glitch model fit for it, corresponding to a time constant of 7.8 ± 0.11 ms.

Fig. 16. Glitch template for the bolometer 217K01. A single time constant model have been fitted to the data. For the best fit, traced in red, the time constant is 7.8 ± 0.11 ms.

In Fig. 17 the values of τ_{short} obtained from the fit of glitches are compared to the shorter optical time constant τ_1 estimated using Jupiter (Tab 4). These are compatible within 1σ for a large number of detectors. The observed discrepancies may be due to the intrinsic degeneracy between time response and beam pattern and the way we break it. Equally, we can imagine different time delays in the detector response depending on where exactly the glitch hits.

The second time constants τ_{long} and τ_2 differ by at least one order of magnitude. The long time constant measured on glitches can be interpreted as a longer thermal link for glitches which hit the immediate surrounding of the bolometer and will not be considered in the following. By contrast, the second optical time constant, τ_2, must be taken into account to accurately deconvolve from the bolometer time response.

6.2. Optical response

6.2.1. Beam pattern model

After deconvolving the Archeops TOI from the bolometer time response, we reconstruct local maps of Jupiter to estimate the beam pattern shape. The beam patterns for the Archeops photometric pixels happen to be asymmetric in particular for the multimode systems (all the 217 GHz detectors but 217K01, 217K02 and 217K05 and the two 545GHz detectors).

We model the main beam shape for each photometric pixel using the *Asymfast* method, described in Tristram et al. (2004). This method is based on the decomposition of the main beam shape into a linear combination of circular 2D Gaussian. This allows us to accurately and simply represent asymmetric beams and to convolve full sky maps with them in a reasonable

Fig. 17. Comparison between glitch and Jupiter short time constant estimates.

amount of time. This is of great interest when producing simulations to estimate the beam transfer function in the spherical harmonic plane (Tristram et al. (2005b)).

The Archeops main beams have been modeled using up to 15 Gaussians. The residuals after subtraction of the model from the Jupiter local maps are less than 5%. Figure 18 shows an example of this multi-Gaussian beam modeling for the photometric pixel 143K03 using 7 circular 2D Gaussians. From top to bottom and from left to right we represent the beam pattern shape from the Jupiter local maps, its multi-Gaussian fit, the residuals and the histogram of the residuals (black line). The latter are shown to be compatible with Gaussian distributed noise (red line in the figure).

Fig. 18. From top to bottom and from left to right, for the photometric pixel 143K03, the beam pattern map in μV from Jupiter observations, its multi-gaussian decomposition using seven 2D Gaussians, the residuals and their distribution which is compatible with Gaussian distributed noise (red line).

Bolometer	fwhm [arcmin]	e	Modes
143K01	11.0	0.76	S
143K03	11.7	0.74	S
143K04	10.9	0.85	S
143K05	11.9	0.78	S
143K07	11.7	0.80	S
143T01	10.2	0.87	S
217K01	12.0	0.72	S
217K02	11.8	0.73	S
217K03	17.5	0.99	M
217K04	15.9	0.75	M
217K05	11.3	0.79	S
217K06	15.1	0.72	M
217T04	14.0	0.65	M
217T06	15.2	0.80	M
353K01	11.9	0.78	S
353K02	12.0	0.79	S
353K03	11.9	0.78	S
353K04	12.0	0.77	S
353K05	12.1	0.71	S
353K06	12.2	0.72	S
545K01	18.3	0.68	M

Table 5. Resolution in terms of the FWHM and ellipticity of the beam pattern for the Archeops photometric pixels in the KS3 flight. See text for details. The optical mode of the bolometers is indicated in the last column: S for single mode bolometers and M for multimode bolometers.

The resolution for each of the photometric pixels has been estimated from a 2D elliptical Gaussian fit to the local beam maps from Jupiter observations. The FWHM values given in Table 5 are the geometric mean value in the two directions. We present as well the ellipticity as computed from the ratio between the minor and the major axis. For monomode systems the beamwidth is about 11 arcmin. The multimode systems at 217 GHz and 545 GHz have larger beams with FWHM ~15 arcmin. The 353 GHz beams are monomode but are by construction illuminating a small part of the primary mirror to have clean polarized beams. A degradation of the beams has been noticed in the KS3 flight compared to ground-based measurements (which are close to the diffraction limit) due to a slight out-of-focus position of the secondary mirror after the crash landing of the KS2 flight.

No specific treatment have been applied in the data analysis to account for far side lobes as from Planck optical modelization they are expected to be at the percent level.

6.2.2. Focal plane reconstruction

The position of each photometric pixel in the focal plane with respect to the Focal Plane Center (FPC) is computed using Jupiter observations. This then allows us to build the pointing of each pixel using the pointing reconstruction as described in Sect. 5. In practice we use the relative positions of the 2D circular Gaussians of the *Asymfast* decomposition to estimate the center of the beam in focal plane coordinates. Fig. 19 shows the reconstruction of the Archeops focal plane in azimuth (along scan) and elevation (across scan) coordinates. The Archeops focal plane is about 2 degrees high and 2.5 degrees wide.

Fig. 19. Focal plane of Archeops reconstructed using Jupiter observations.

7. Description and subtraction of systematics

In this section we describe in details the main systematic effects on the Archeops data as well as the methods and algorithms used for their subtraction. Because of the circular Archeops scanning strategy the sky signal shows up on the data at frequencies which are multiples of the spin frequency. This naturally leads to three distinct regimes in frequency. First, the very low frequency components at frequencies well below the spin frequency ($f < 0.01$ Hz) which are mainly due to $1/f$-like noise and systematics. Second, the spin frequency components ($0.03 < f < 3$ Hz) at frequencies which contain most of the sky signal of interest. And finally the high frequency components at frequencies much larger than the spin frequency ($f > 10$ Hz) which are dominated by detector noise.

Fig. 20. Left column: from top to bottom, raw Archeops data in μV (black curve) and reconstructed very low frequency drift (red curve) for the 143K03, 217K06, 353K01 and 545K01 bolometers respectively. Right column: from top to bottom, Archeops data in μV after removal of the very low frequency parasitic signals for the 143K03, 217K06, 353K01 and 545K01 bolometers respectively.

7.1. Very low frequency systematics

At very low frequency the Archeops data are dominated by systematics coming mainly from temperature fluctuations of the three cryogenic stages at 100 mK, 1.6 K and 10 K and from the variation of air mass during the flight due to changes in the balloon altitude. The left column of Fig. 20, from top to bottom, shows the raw Archeops data for the 143K03, 217K06, 353K01 and 545K01 bolometers in the period from 14h00 to 29h00 UT time. We observe a very low frequency drift in the data which is very well correlated within bolometers and also with the low frequency components in the housekeeping data from thermometers placed at each of the cryogenic stages and with measurements of the altitude of the balloon.

This drift is removed via a decorrelation analysis using as templates the housekeeping data described above and a fifth order polynomial defined in the time interval of interest. To compute the correlation coefficients we first smear out and undersample both the Archeops data and the templates, and then, we perform a linear regression. A final estimate of the drift is obtained from the best-fit linear combination of the templates which are previously smoothed down to keep only the very low frequency signal. In the left column of Fig. 20 we overplot in red the reconstructed very low frequency drift for the four Archeops bolometer. In the right column of the figure we show the Archeops data after subtraction of the low drift estimate which reduces the signal amplitude by a factor of 50. Although the decorrelation procedure is very efficient, we can still observe a correlated low frequency parasitic signal between bolometers. To avoid the mixing up of the bolometer signals at this stage of the processing of the data, this effect is considered within the map making pipeline described in Sect. 10.

7.2. Spin frequency systematics

The Archeops data at the few first multiples of the spin frequency are particularly important. They contain the large angular scale signal of the sky whose mapping is one of the main purposes of the Archeops experiment. At these frequencies in addition to the CMB anisotropies and the Galaxy, two main components can be identified, the CMB dipole and the atmospheric emission. Although the former is critical for the calibration of the Archeops data at 143 and 217 GHz (see Sect. 9.1) for this analysis we consider both of them as systematics.

As above, we perform a decorrelation analysis to remove these parasitic signals. A template for the dipole in mK_{CMB} is simulated using the COBE best dipole solution (Smoot et al. (1991)) and the local velocity vector during the flight. The atmospheric contamination is mainly due to the variation of the air mass induced by changes in the altitude and the pointing elevation of the payload. As templates for this effect we use the housekeeping data corresponding to measurements of the altitude of the balloon and the reconstructed elevation of the focal plane. To compute the correlation coefficients, we smear out and undersample both the Archeops data and the templates and perform a linear regression. The final estimate of the spin frequency systematics are obtained from the best-fit linear combination of templates. The left column of Fig. 21 shows from top to bottom, the Archeops data in μV (black curve) and the reconstructed spin frequency systematics (red curve) for the 143K03, 217K06, 353K01 and 545K05 bolometers respectively. We observe that at the low frequency channels the dipole contribution (exactly at the spin frequency) dominates while at the high frequency the atmospheric emission is much more important and dipole becomes negligible.

The spin frequency systematic estimate is then filtered out in the range of frequency of interest, low passed to remove very low frequency drifts in the templates and high pass to reduce the noise in the templates, and subtracted from the Archeops data. The right column of Fig. 21 shows the Archeops data for the four bolometers before and after subtraction of the spin frequency systematic estimates. After subtraction we clearly observe at all frequency the Galactic signal. This shows up as peaks at each revolution and of increasing amplitude with increasing frequency channel. This is better shown on Fig. 22 where we represent the power spectrum in $\mu V \sqrt{Hz}$ of the Archeops time ordered data before (black curve) and after (red curve) subtraction of the spin frequency systematics. At 143 and 217 GHz the dipole contribution appears clearly as a peak at the spin frequency before subtraction. After subtraction we clearly distinguish the Galactic signal which dominate the spectrum at 353 and 545 GHz.

Beside the atmospheric signal which is correlated to templates there is a residual parasitic atmospheric signal. The latter can be qualitatively reproduced by simulating turbulent atmospheric layers drifting across the Archeops scanning beam. Typical gradients of half a mK_{RJ} over 10 degrees azimuth are observed at 545 GHz with an evolving period of 1000 seconds.

7.3. High frequency systematics

The Archeops data present, at frequencies $f > 5$ Hz, parasitic noise which shows up on the time domain as noise bursts which are neither stationary nor Gaussian. In the Fourier plane this parasitic signal is observed in the form of well defined correlated structures or peaks. This parasitic noise is very likely related to microphonic noise. Its contribution to the data was significantly reduced in the KS3 flight with respect to the KS1 flight by increasing the distance between the payload and the

Fig. 21. Left column: from top to bottom, Archeops data in μV (black curve) and reconstructed spin frequency systematics (red curve, including the CMB dipole and atmospheric emission) for the 143K03, 217K06, 353K01 and 545K01 bolometers respectively. Right column: from top to bottom, Archeops data in μV before (black curve) and after (red curve) removal of the spin frequency systematics for the 143K03, 217K06, 353K01 and 545K01 bolometers respectively.

Fig. 22. From left to right and from top to bottom power spectrum in μV $\sqrt{Hz}$ of the time ordered Archeops data before (black curve) and after (red curve) subtraction of the spin frequency systematics for the 143K03, 217K06, 353K01 and 545K01 bolometers.

Fig. 23. From left to right and from top to bottom power spectrum in μV $\sqrt{(}Hz)$ of the low frequency processed Archeops data before (in black) and after (in red) decorrelation from the high frequency noise for the 143K03, 217K06, 353K01 and 545K01 bolometers respectively.

spinning motor. The latter was placed far away in the flight chain with no rigid link between them. Fig. 23 shows in black the power spectra of the Archeops low frequency processed data for the 143K03, 217K06, 353K01 and 545K01 bolometers. Structures around 15, 22, 40 and 50 Hz are clearly visible in the power spectrum. We can also observe a peak at 28.5 Hz in the power spectrum of the 353K03 bolometer data.

These structures are also observed on the power spectrum of the data from the focal plane thermometers and from the blind bolometer. Moreover, they are in phase correlated, in the temporal domain, with the bolometer ones. This fact allows us to efficiently remove this parasitic noise via a decorrelation analysis in the Fourier plane using as templates the housekeeping data for the focal plane thermometers and the blind bolometer.

Assuming a linear model we can write the Fourier transform of the parasitic signal for the bolometer i as $B_i^{par}(\nu) = F_i(\nu) \times T(\nu)$ where T represent the templates described above and $F_i(\nu)$ is a frequency dependent correlation coefficient. As the parasitic signal is both well localized in time and in frequency, we perform a regression analysis in the Fourier plane using the windowed Fourier transform over time intervals of size L in order to compute the correlation coefficient $F_i(\nu)$. To maximize the efficiency of the algorithm and to limit the subtraction of sky signal which may be accidentally correlated with the templates we apply the decorrelation analysis only in a few predefined frequency intervals where the parasitic signal dominates. Further to obtain a robust estimate of the correlation coefficient we average it over N time intervals so that for each of the frequency intervals it reads

$$F_i(\nu) = \frac{\sum_{k=0}^{N-1} \tilde{B}_i^k(\nu)\tilde{t}^{k^*}(\nu)}{\sum_{k=0}^{N-1} \tilde{t}^k(\nu)\tilde{t}^{k^*}(\nu)}. \quad (11)$$

where $\tilde{f}$ represents the Fourier transform of function f.

The estimate of the high frequency parasitic noise is then subtracted from the data in the Fourier plane. We repeat this analysis for each of the available templates. The choice of the parameters of the method, i.e L, N, results from a trade-off : we want to minimize the parasitic power in the TOI spectrum, but we also want that the CMB signal remained unaffected by the process. Simulations leads to a best choice of parameters $L = 32768$ samples and $N = 32$ to get a CMB power reduced by less than 1%.

In Fig. 23 we plot the power spectra for the bolometers 143K03, 217K06, 353K01 and 545K01 before and after subtraction of the high frequency parasitic signals. We observe that the parasitic signal is significantly reduced in particular at the lowest frequencies. However for most of the bolometers around 40 Hz the processing although efficient in removing the systematic effect is not satisfactory (residuals are much larger than for lower frequencies) and therefore in the following the Archeops TOIs are high pass filtered at 38 Hz before any scientific analysis. We also observe that, in some of the bolometers very well localized peaks in the spectrum are not removed in our process. These peaks are manually characterized and the signal at their frequencies is removed in the Fourier domain for all Archeops bolometers.

8. Data quality checks and noise properties

As discussed in the previous section the Archeops data are affected by parasitic microphonic noise at high frequencies and by other unidentified systematics in the whole frequency range. None of them are neither stationary nor Gaussian and their contributions vary significantly among bolometers. In this section we briefly describe how we performed the selection of the best bolometers, in terms of level of residual systematics and of noise properties, which are used for the construction of the Archeops sky maps presented in Sect. 10.

8.1. Time-frequency analysis of the Archeops data

We have performed a time-frequency analysis of the Archeops data using the Discrete Wavelet Packet Transform (DWPT) as described in Macías–Pérez & Bourrachot, (2006). The top left

Fig. 24. Left column: from top to bottom, time-frequency representation of the 217T04 bolometer data and of the expected Galactic signal for it. Right column: same for the 217K04 bolometer.

Fig. 25. *Top*: Average wavelet power spectrum in μV of the TOD of the 217K04 Archeops bolometer as a function of frequency computed from its DWPT *Bottom:* Time evolution of the power spectrum of the TOD of the 217K04 Archeops bolometer computed from its DWPT.

panel of figure 24 shows the power distribution in the time-frequency plane for the data of the 217T04 bolometer. At low frequency and because of the particular scanning strategy of Archeops, we can observe spikes and some broader structures which correspond mainly to Galactic signal. This is clearly shown by the bottom plot where we trace the expected Galactic signal for this bolometer. Also at low frequency we distinguish the atmospheric residuals and the $1/f$-like noise on the bolometer. We can further observe from 20 to 40 Hz structures which vary on time being particularly strong around 21h00 UT time. These structures are residuals, after subtraction, of the high frequency systematics described before. Notice that the level of systematics is significantly larger than the high frequency noise making this bolometer useless for scientific purposes.

On the top right panel of figure 24 we present the time-frequency analysis of the 217K04 bolometer. As above, we can clearly distinguish at low frequencies the Galaxy contribution whose template is represented in the bottom right panel. We observe for this bolometer no intermediate frequency structures as for the previous bolometer. The systematic contribution has significantly reduced by the high frequency subtraction and the residuals are well below the high frequency noise. This simple but efficient analysis allows us to exclude from the further processing those bolometers which present either strong or highly time variable systematic residuals. Typically the Trapani bolometers presented a large amount of contamination and were excluded. We also realized that the noisier bolometers were in general more affected by residual systematics.

8.2. Long term non-stationarity of the noise

On the top panel of Fig. 24, at very high frequency we can distinguish a slow decreasing of the noise power with time which is the main cause of non stationarity in the Archeops data. This is due, as discussed in Sect. 7.1, to the sudden increase of temperature of the Archeops cryostat when taking off and to its slow cooling down to the nominal value of about 95 mK during the flight. To account for this non stationarity we have modeled the Archeops data as a time modulated-stationary wavelet process (Macías–Pérez & Bourrachot, (2006)). These processes correspond to a continuous generalization of piecewise stationary processes. They are described by two main variables : the mean power spectrum of the data and a time varying function, $\sigma(t)$, which account for the time variations of the power spectrum.

Figure 25 shows on the top and bottom panels the time averaged wavelet spectrum and the $\sigma(t)$ function respectively for the noise of bolometer 217K04. On the top plot we can clearly distinguish the increase of noise power with frequency which is due to the deconvolution from bolometer time response. On the $\sigma(t)$ function, there are two distinct regimes corresponding first to a fast cooling of the cryostat in the first two hours and then to a roughly constant temperature of the focal plane during the last 10 hours of flight. Notice that our estimate of $\sigma(t)$ is noisy and therefore for further processing we generally smooth it. We can also observe variations on $\sigma(t)$ above the noise limit for the second regime, that, although small with respect to those on the first two hours of flight, need to be taken into account in any further processing.

8.3. Gaussianity of the noise

Up to now, we have only considered the power spectrum evolution to define the level of stationarity of the data. To be complete in our analysis we have first to characterize the Gaussianity of the noise distribution function and second to check its evolution with time. In practice and to reduce the uncertainties in the analysis it is more convenient to proceed the other way around.

We have implemented a Kolmogorov-Smirnov test in the Fourier domain to check the evolution with time of the noise distribution function of each of the bolometers. Notice that the intrinsic bolometer noise can be considered Gaussian to a very good approximation and therefore any changes on the distribution function of the noise will indicate the presence of significant residuals from systematics. We work in the Fourier domain both to speed up the calculations and to isolate the noise, which dominates at intermediate and high frequencies, from other contributions like the Galactic and atmospheric signals. We have performed the test in consecutive time intervals of about 7 minutes which we compare two by two. We divided the frequency space in bins of 1 Hz. The test is considered to fail when the probability of having a greater Kolmogorov-Smirnov statistics under the equal distribution hypothesis is less than 1%.

The results of the test for the KS3 bolometers 143K03, 217K06, 353K06 and 545K01 are shown on Fig. 26. The white points represent failing intervals in the time-frequency domain. Between 16h00 and 27h00 UT, the test is successful except for the lowest frequency bins ($f \leq 10$ Hz), in which the Galactic and atmospheric signals, which are neither Gaussian nor stationary, dominate. We notice that elsewhere the number of points where the test fails is no more than 1% of the total, that is, exactly what is expected under the hypothesis of no time evolution of the distribution function. Moreover, they do

not exhibit any clustering. Around 28h00 UT, the sunrise on the gondola induces strong time evolution due to the heating of the 10 K stage.

Fig. 26. From top to bottom, results of the Kolmogorov-Smirnov test on the bolometers 143K03, 217K06, 353K06 and 545K01 respectively. The white polygons correspond to intervals in the time frequency plane where the test is considered to fail (see text for details).

In the range from 16h00 to 27h00 UT, as the properties of the distribution function does not vary, we can globally study the Gaussianity of the noise. For this purpose we have implemented a simple test in the Fourier domain by fitting a Gaussian to the histogram of the coefficients of the Fourier decomposition of the time ordered data which were binned in 1 Hz intervals as above and computing the χ^2 value for the fit. We consider the test to fail if for Gaussian distributed data the probability of having a greater reduced χ^2 that the one measured is significantly below 5 %. Figure 27 shows the results of the test for the KS3 bolometers, 143K03, 217K06, 353K06 and 545K01. We trace the reduced χ^2 as a function of the frequency bin. In dark and light blue we overplot the χ^2 values for which the probability of having a larger one considering a Gaussian distribution are 95 % and 5 % respectively. The reduced *chi*2 measured are almost everywhere below or around the 5 % limit, except in the first frequency bin where the Galactic signal, highly non Gaussian, dominates. We can therefore consider that the data are in a first approximation compatible with Gaussianity.

8.4. Noise power spectrum estimation and simulations

We have performed noise simulations, which we call constrained realizations of noise, to fill the gaps in the data. In this case we use a simple algorithm. First, we reconstruct the low frequency noise contribution via interpolation within the gap using an irregularly sampled Fourier series. Finally, we compute the noise power spectrum locally (in time intervals of about 1 hour around the gap) at high frequency and then we produce a random realization of this spectrum. Notice that we are only interested in keeping the global spectral properties of the data. Moreover, the gaps are in general very small in time compared to the piece of the data used for estimating the power spectrum and therefore this simple approach is accurate enough.

For the first estimate of the CMB angular power spectrum with the Archeops data (Benoît et al. (2003a)) we needed an accurate estimate of the noise angular power spectrum. For this purpose, we have estimated the time power spectrum of the noise for each of the Archeops bolometers using the algorithm described in Amblard & Hamilton (2004). This algorithm relies on the iterative reconstruction of the noise by subtracting in the TOD an estimate of the sky signal. The latter is obtained from a coadded map which at each iteration is improved by taking into account the noise contribution. From the reconstructed noise timeline we can then obtain for each bolometer both the average noise power spectrum and the $\sigma(t)$ function described in Sect. 8.2. Since the noise in the Archeops data can be considered as Gaussian distributed (Sect. 8.3) these two quantities are enough to simulate noise timelines using the algorithm presented in Macías–Pérez & Bourrachot, (2006). The fake timelines can then be projected into maps for the estimate of the noise angular power spectrum. In general a few hundreds simulations are needed to obtain a reasonable estimate.

8.5. The best bolometers

From the above analysis of the Archeops noise we have chosen for each frequency band those bolometers for which the residual systematics are well below the noise level. For the CMB channels at 143 GHz and 217 GHz the selected bolometers (143K03, 143K04, 143K05, 143K07, 217K04 and 217K06) correspond to the more sensitive ones going from 94 to 200 $\mu K\ s^{1/2}$. At 353 GHz the bolometers were all of similar quality and we keep all of them. At 545 GHz only one bolometer was available, 545K01.

9. Calibration

We describe in this section the global absolute calibration and intercalibration of the Archeops data. The former is performed using three different types of calibrator : the CMB dipole, the Galaxy and the planets Jupiter and Saturn. At low frequencies (143 and 217 GHz) the dipole is the best absolute calibrator. At higher frequencies we need to use the Galaxy because the dipole signal is too faint with respect to the noise and systematics.

9.1. CMB dipole

At low frequencies, the CMB dipole is a very good absolute calibrator (Piat *et al.* (2003), Cappellini et al. (2003)) and therefore it constitutes the primary absolute calibration of the Archeops data. Here we use the total dipole which is the sum of the solar dipole (constant in time) and the Earth induced dipole (with annual variations due to the Earth change of velocity) computed at the time of flight. Indeed, the dipole calibration has the following advantages: 1) the dipole is spread over the all sky and thus it is always present whatever the pointing, 2) it is much brighter (typically a factor of 100) than the CMB anisotropies, but still faint enough so that non linearity corrections are usually not needed, and finally 3) it has the same electromagnetic spectrum as the CMB anisotropies so that no color corrections need to be applied. The only drawback is that we must assume a constant response for the instrument throughout a wide range of angular scales, *i.e.* an extrapolation from $\ell = 1$ to 1000. The dipole being an extended source we need to account for the beam and the spectral transmission of each of the detector to generate the point source calibration.

Fig. 27. From left to right and up to bottom, maximum reduced χ^2 (97 d.o.f) of the Gaussian fit of the histogram of the Fourier coefficients of the Archeops data for the 143K03, 217K06, 353K06 and 545K01 bolometers respectively. In dark and light blue we overplot the χ^2 values for which the probability of having a larger one considering a Gaussian distribution are 95 % and 5 % respectively. (see text for details on the analysis)

In the Archeops case, the dipole signal is expected to contribute only to the fundamental rotation frequency $f_{\rm spin}$. However, the drift of the rotation axis during the flight leads to a broadening of the f_{spin} dipole contribution which needs to be taken into account. Furthermore, as discussed in Sect. 7.2, other signals show up at the spin frequency including both Galactic and atmospheric signals. To account for these, we compute the total dipole calibration coefficients from the correlation analysis described in Sect. 7.2. We actually produced templates of the Galactic emission using extrapolation of the dust emission to the Archeops frequency (Finkbeiner et al (1999)) and templates for the atmospheric emission using the housekeeping data from the altitude and elevation of the balloon. The template for the total dipole in time domain was obtained by deprojecting, using the Archeops pointing, a simulated CMB dipole map for which the dipole amplitude and direction were taken from the WMAP results (Bennett et al. (2003)). The left panel of Fig. 28 shows the simulated total dipole map in Galactic coordinates for the Archeops coverage and centered in the Galactic anticenter. On the right panel we plot the Archeops reconstructed CMB dipole for the 143K03 bolometer. We observe a very good agreement between the two maps but for some stripes when crossing the Galactic plane and on the North at high Galactic latitude.

Indeed, the CMB dipole is detected with a signal to noise better than 500 for 12 hours of data on the 143 and 217 GHz channels. The errors on the dipole calibration coefficients come mostly from systematic effects. We produced several versions of the calibration coefficients by changing the templates used in the fit. We noticed that the result is very stable with respect to even the most extreme cases. From those tests, we can deduce that the overall uncertainty (1 σ) is 4 % (resp. 8 %) for the 143 (resp. 217) GHz photometric pixels. The larger uncertainty for the 217 GHz channel reflects the spectrum of the atmospheric contamination. Notice that the dipole calibration is performed at the early stages of the analysis before removing the spin frequency systematics (see section 7). When applied to the 353 GHz channel, there is a residual contaminant at the same level as the dipole. Considering the 545 GHz channel in the analysis can help in this case and allows finding the dipole calibration coefficient at 353 GHz in agreement with the Galactic calibration coefficients within 20 % as described below.

9.2. The Galaxy

At high frequencies 353 and 545 GHz, the Galactic emission has to be used to calibrate the Archeops data. The best data, in term of spectral coverage and absolute calibration accuracy, are the FIRAS spectra (Mather et al. 1990). FIRAS, on board the COBE satellite, is a scanning Michelson interferometer that has provided low-resolution spectra in a low (2 - 20 cm^{-1}) and high (20 - 100 cm^{-1}) frequency band, for 98.7% of the sky. For individual pixels, the signal-to-noise ratio of the FIRAS spectra is about 1 at high Galactic latitude and $\sim$50 in the Galactic plane. The FIRAS maps used here were obtained by fitting each FIRAS spectrum using a modified Black Body with a ν^{β} emissivity law and extrapolating the fit at Archeops frequencies. Since we are searching for the best representation of the data and not for physical dust parameters, we restricted the fit to the frequency range of interest (this avoids the need for a second dust component, of the type proposed by Finkbeiner et al (1999)). The FIRAS brightness maps are then converted to photometric maps with the flux convention of constant νI_{ν}. To be compared to the FIRAS maps and to maintain the best possible photometric integrity, the Archeops data are convolved by the FIRAS beam and put into the FIRAS Quadrilateralized Spherical Cube (QSC). At this stage, we have Archeops maps at the FIRAS resolution that can be directly compared to the FIRAS maps at the Archeops frequencies to derive the Galactic calibration factors.

Due to its high signal-to-noise ratio and its extension, the Galactic plane is the best place to derive the calibration factors. We compute Galactic latitude profiles of both maps ($|b| < 30^o$) at selected longitudes and perform a best straight-line fit to the Archeops-FIRAS profile correlation from which we derive the calibration factor and its error bar. An example of this fit is shown on Fig. 29 where we observe a linear correlation between the Archeops and FIRAS profile intensities. The whole calibration process gives calibration factors with statistical errors of about 6 %. Details on the whole calibration process are given can be found in Lagache & Douspis (2006).

Fig. 29. FIRAS/Archeops Galactic profiles correlation on the Galactic plane (bolometer 353K01 at 353 GHz). Fitting a straight-line gives the calibration factor.

Our procedure has been extensively tested. We have applied the calibration scheme to the comparison between the FIRAS and DIRBE data at 140 and 240 μm and found results in very good agreement with those of Fixsen et al (1997). We also tested our procedure on the Finkbeiner et al (1999) maps, although these maps exclude the Galactic plane below $|b|$=7^o. We obtain gain differences which are less than 6% across the Archeops frequencies. We also used Archeops maps

Fig. 28. From left to right, simulated and reconstructed CMB dipole maps for the Archeops 143K03 bolometer centered at the Galactic anticenter. To reconstruct both dipole maps the timelines have been band pass filtered. This introduces discontinuities on the maps due to the scanning strategy.

obtained using different low-frequency filters to test the effect of the filtering on the calibration. We found that it modifies the calibration factors by only ~3%.

Although the calibration on the Galaxy is less accurate for the low-frequency than for the high-frequency channels of Archeops, we compare the CMB dipole and Galaxy calibration factors on Fig. 30. We observe a good agreement between both calibrations, with a mean ratio of the calibration factors lower than 1.05 and all of them compatible with 1 within the 1σ error bars. This clearly demonstrates the robustness of the methods used for the extended emission calibration and the consistency of the data reduction from TOIs (dipole calibration) to maps (Galactic calibration).

Fig. 30. Comparison of the Galactic and Dipole calibration factors (in mK/μV). The error bars (both statistical and systematic) are of about 4% and 8% for calibration on the dipole at 143 and 217 GHz respectively and from 6% to 15% for the calibration on the Galaxy.

9.3. Jupiter calibration

We have also performed a point source calibration using the measurements at the two independent crossings of the planets Jupiter and Saturn (5 times fainter than Jupiter). For this purpose we proceed as follows: 1) We obtain the beam pattern shape from the Jupiter measurements after deconvolution from the bolometer time response 2) We compute the flux of the sources (in μV) using pixel photometry up to a radius of 40 arcmin starting from the center of the beam pattern. 3) Finally, we compare the fluxes to a model of the temperature emission of the sources (Moreno (1998)) that reproduces radio observations of Jupiter and Saturn from 20 to 900 GHz. Taking into account uncertainties on the model, absolute errors on point source calibration with Jupiter are estimated to be ~12%.

The ratio between Jupiter and Saturn flux measurements at a given frequency does not depend on the absolute instrument calibration. We find ratios of 0.97 ± 0.016 and 1.02 ± 0.020 at 143 and 217 GHz respectively which are not compatible with the one measured by Goldin et al. (1997) (0.833 ± 0.012) at similar frequency (171 GHz). Due to the large brightness of Jupiter (about 1 K_{RJ} equivalent brightness) we expect some non-linearity on the bolometer response which could be the cause of this difference. This problem in addition to the uncertainties on the knowledge of the beam pattern and in particular of the far side lobes could also explain the small discrepancies between the Jupiter calibration and the dipole calibration as shown on Fig. 31.

Fig. 31. Comparison of the point source (Jupiter and Saturn) and dipole calibration factors. The error bars are about 4% and 8% for calibration on the dipole at 143 and 217 GHz respectively and about 12% for the calibration on the sources (essentially due to the uncertainty of the thermal emission model).

9.4. Intercalibration

Bolometer	relative calibration (μV/μV)	error (stat.)
143K01	1.16	2.1%
143K03	1	-
143K04	1.63	2.3%
143K05	1.15	1.8%
143K07	1.39	1.9%
143T01	2.06	2.3%
217K01	1.80	1.1%
217K02	1.72	0.8%
217K03	9.09	2.5%
217K04	0.903	0.7%
217K05	3.21	1.2%
217K06	1	-
217T04	1.50	1.1%
217T06	1.02	1.02%
353K01	1	-
353K02	1.13	0.68%
353K03	1.19	0.70%
353K04	1.02	0.70%
353K05	1.20	0.79%
353K06	1.05	0.78%

Table 6. Relative calibration coefficients and their relative statistical errors from Galactic profiles at constant Galactic longitude.

The polarization signal for experiments like Archeops is reconstructed, in a first approximation, from the differences between pairs of bolometers (see Sect. 10.3). Therefore the accuracy on this reconstruction is very sensitive to the relative calibration between bolometers. In the case of the Archeops 353 GHz polarized channels, the absolute calibration on the Galaxy presented above is not accurate enough for the direct reconstruction of the polarized maps. Thus, we have implemented a relative calibration algorithm based on the inter-

comparison, for all bolometers in the same channel, of Galactic profiles at constant Galactic longitude. This algorithm has also been applied to the unpolarized channels at 143, 217 GHz as a cross check of the absolute calibration analysis.

Assuming N bolometers per channel we can measure, N Galactic profiles as a function of the Galactic latitude, b,

$$s_j(b) = \alpha_j \overline{s}(b) + n_j(b)$$

where α_j and $n_j(b)$ are the intercalibration coefficient and noise contribution for the bolometer j respectively, and $\overline{s}(b)$ is the true Galactic profile at the frequency of interest. Our algorithm, which is based on a χ^2 minimization constrained via Lagrange's multipliers, estimate simultaneously the intercalibration coefficients and the mean Galactic profile. This algorithm is described in details on appendix A. We have performed robustness test to validate the algorithm. In particular we have checked that the results are not affected by the choice of constraint and that the analytical error bars obtained for the intercalibration coefficients are reliable.

Fig. 32. From left to right, Archeops Galactic profiles in μV at constant Galactic longitude respectively before and after the intercalibration for the 353 GHz bolometers.

The algorithm was applied to the Archeops data which were previously processed as described in the previous sections. The profiles were obtained by averaging the signal samples within latitude bins. The errors are computed assuming that the noise is white, uncorrelated between bolometers and stationary. The noise of each sample is estimated from either data outside the Galactic plane ($|b| \geq 25°$) or high-pass filtered data above 10 Hz (where Galactic signal is negligible). Results are very similar (differences between the two methods are less than 3%, inducing negligible difference in intercalibration coefficients) in the two cases. Finally, care has been taken on keeping the same sky coverage for all bolometers when computing the Galactic profiles.

For the polarized channel the presence of strongly polarized regions on the sky may affect the computation of the intercalibration coefficients. To avoid this, we proceeded in two steps. First, we compute the relative calibration coefficients and mean Galactic profile on the full common sky area for the six polarized bolometers. Using these coefficients we build polarization maps and label strong polarized areas which are then excluded from the analysis. We then build again the Galactic profiles and recompute the relative calibration coefficients. After two iterations, we observed that the estimates of the intercalibration coefficients are stable. We show on Fig. 32 the results of this analysis for the 353 GHz channel. From left to right we plot the Galactic profiles before and after intercalibration respectively. We observe that the intercalibration is achieved with a high degree of precision.

Final results on the intercalibration coefficients for the Archeops data are given in Tab. 6 for all the bolometers at 143 GHz, 217 GHz (unpolarized) and 353 GHz (polarized). The 1σ statistical errors on the relative calibration coefficients are at most 2.5% and always below 1% for the polarized channel. Error bars are smaller at high frequency because the Galaxy signal is stronger.

9.5. Overall sensitivity

Using the observed response and white noise level of the bolometers, we can now estimate the global efficiency of the instrument during the KS3 flight. Table 7 gives the instrument sensitivities in various units at the timeline level. This places Archeops within the best range of instrumental instantaneous sensitivities for millimetre continuum measurements. We also compute the averaged sensitivity, quoted in Tab. 8, by using a total integration time of 12 hours and a total sky coverage of 30 %. In this case Archeops is not within the best experiments because the sensitivity per pixel is diluted by the large covering area needed for reconstructing the large angular scales on the sky.

10. The Archeops sky maps

In this section we finally describe how we obtain submillimetre sky maps from the Archeops timelines and pointing information. First and prior to projection we remove low frequency drifts on the Archeops timelines via a destriping algorithm. Then, these timelines are processed in three different ways to produce after projection: CMB, Galactic intensity and polarization maps.

10.1. Destriping

Even after the subtraction of the very high and low frequency identified systematic effects from the data, we can observe residual stripes on the Archeops simple coadded maps. These are mainly due to low frequency drifts in the data coming from atmospheric residuals and other thermal backgrounds. Notice that there is no electronic $1/f$ component because of the AC bolometer modulation scheme (see Sect. 4.2). To remove those drifts we have implemented a destriping algorithm (Bourrachot (2004)) making the assumption that the scanning direction is generally not related to the orientation of the structures on the sky. To destripe we compute a low frequency baseline in the timelines by minimizing the ratio between the rms in the cross-scan and in the in-scan directions directly from the time ordered data (no reconstruction of maps is needed). To represent the baseline we use a basis of localized functions $U_k(t)$ where

$$\begin{aligned} U(t) &= sinc\left(\frac{\pi t}{\Delta}\right)\exp\left(-\frac{t^2}{2\Delta^2\sigma^2}\right) \\ U_k(t) &= U(t-t_k) \\ t_k &= k\Delta. \end{aligned} \qquad (12)$$

These functions are regularly sampled and contain only frequencies lower than $1/(2\Delta)$.

The minimization is performed outside the Galactic plane over boxes with sizes related to Δ (typically a few tens of square

Freq.(GHz)	N_{bol}	μK$_{\rm RJ}$/Hz$^{1/2}$	MJy/sr/Hz$^{1/2}$	μK$_{\rm CMB}$/Hz$^{1/2}$	$10^6 y$/Hz$^{1/2}$	μK$_{\rm CMB}$.s$^{1/2}$
143	6	50	0.031	87	23	61
217	7	39	0.056	127	286	90
353	6	82	0.315	1156	132	817
545	1	77	0.702	9028	495	6384

Table 7. The Archeops KS3 in–flight timeline sensitivities per channel. The best bolometers on each frequency channel are optimally combined (N_{bol}) to obtain a sensitivity at the instrument level. From left to right the units correspond to a Rayleigh–Jeans spectrum, then a constant νI_ν spectrum, and a CMB spectrum. Sensitivity to the SZ effect is measured with the dimensionless y Compton parameter. To convert to 1 σ and to one second integration, we can simply divide by $\sqrt{2}$: see an example in the last column.

Freq.(GHz)	N_{bol}	μK$_{\rm RJ}$	MJy/sr/Hz	μK$_{\rm CMB}$	$10^6 y$	Jy
143	6	57	0.036	98	27	1.2
217	7	44	0.064	144	325	2.2
353	6	94	0.358	1312	150	12.1
545	1	87	0.797	10251	562	27.0

Table 8. The Archeops KS3 in–flight map sensitivities per channel. The best bolometers on each frequency channel are optimally combined (N_{bol}) to obtain a sensitivity at the map level. A square pixel of 20 arcminutes is taken to compute the average 1 σ noise. KS3 flight roughly covered 30 % of the total sky, which represent 110,000 pixels. A bolometer has observed a pixel on the map during an average time of 0.4 seconds.

Fig. 33. Left: Power spectrum of the time ordered data of the bolometer 545K01 before (black) and after (red) destriping. Right: Zoom-in of the left plot at first multiples of the spinning frequency.

degrees). The cut on the Galactic plane is obtained from a Galactic mask derived from Galactic template maps computed at the Archeops frequencies (using Finkbeiner et al (1999)). The algorithm is applied in steps of decreasing Δ (4000, 1000, 500 and 300) to focus on different frequency ranges. In any case, data at frequencies above 1 Hz are not affected by this method. Prior to this process we generally apply a classical destriping algorithm based on the minimization of the variance per pixel in the maps to produce a first approximation of the baseline and in particular of the lower frequency components (below 0.7 Hz).

We have applied the destriping algorithm to simulated Archeops data at 217 and 545 GHz including correlated noise at low frequencies and Galactic and CMB emissions. No bias has been observed in the estimation of the Galactic signal. For the CMB the power is reduced by at most 5 %. The full destriping transfer function in the multipole space is presented in Tristram et al. (2005b).

An example of the application of the destriping procedure to the Archeops data is shown on Fig. 33. On the left panel, we represent the power spectrum of the 545K01 bolometer data before (black) and after (red) application of the destriping method. We observe that the noise is reduced significantly at low frequencies and in particular the spectrum flattens. Further we can observe from the right plot that power spectrum signal at the few first multiples of the spinning frequency are much broader before destriping. We can conclude, by comparing the 353 and 545 GHz data, that this extra structures come mainly from the atmospheric emission.

10.2. Specific processing for Galactic maps

10.2.1. Atmospheric contamination

For producing Galactic maps from the Archeops data we need first to remove the residual parasitic atmospheric noise. The destriping algorithm described above, although very efficient at frequencies lower than 1 Hz, can not fully eliminate it. From Fig. 33 we observe that the latter shows up on the power spectrum of the time ordered data as residuals at the spin frequency multiples. This also produces two well defined structures, between 0.9 and 1.6 Hz, in the power spectrum. This is shown on Fig. 34 where we plot the power spectrum of the TOI for the 143K03, 217K04, 353K01 and 545K01 bolometers. Notice that the parasitic noise shows a common spectrum shape for all the Archeops bolometers and that its total intensity increases with the frequency of observation.

To estimate this parasitic atmospheric noise and remove it from the data we have used a modified version of the MCMD-SMICA component separation algorithm (Delabrouille et al. (2003)) which can work directly on time ordered data. We have assumed a very simple linear model for the Archeops timelines with three main components: Galactic

Fig. 35. Power spectrum in arbitrary units of the parasitic-like component for the MDMC analysis of the bolometer 353K01 for different time intervals.

Fig. 34. From left to right and from top to bottom MDMC decomposition of the Archeops data at intermediate frequencies for the 143K03, 217K04, 353K01 and 545K01 bolometers. The black, blue and red line correspond to power spectrum in arbitrary units of the raw data, the parasitic-like and the Galactic-like contributions respectively.

emission, atmospheric emission and Gaussian instrumental noise. In the time ordered data the Galactic emission is weak relative to the noise. Therefore, to improve the convergence of the algorithm we have used as inputs, apart from the Archeops data, fake timelines of Galactic emission extrapolated to the Archeops frequencies from the IRAS maps using model 8 in Finkbeiner et al (1999). Finally, to reduce the noise contribution we have restricted our analysis to the frequency range from 0.03 to 2.5 Hz. The main results of this analysis for the 143K03, 217K04, 353K01 and 545K01 bolometers are presented in Fig. 34. The blue and red curve are the reconstructed atmospheric and Galactic emissions. We observe that the reconstructed emission reproduces very well the two structures on the power spectrum and also contributes to the multiples of the spin frequency. As we expect the atmospheric emission to vary with time we have performed this analysis for different intervals. As shown in Fig. 35 the power spectrum of the atmospheric parasitic noise does not change significantly neither in shape nor in intensity. From these results we have constructed a template of the atmospheric emission which is subtracted from the data via a simple decorrelation analysis as described in Sect. 7.

10.2.2. Galactic maps

The final Archeops Galactic maps, presented in Fig. 36, are produced in the Healpix pixelization scheme by simple coaddition of the previous processed timelines which are previously band-pass filtered. The low-pass filtering allows us to both remove spurious high frequency noise in the data (see section 7) and avoid aliasing on the final maps. The high-pass filtering keeps frequencies above 0.03 Hz and to reduce ringing we first mask the brightest Galactic regions and fit an irregularly sampled Fourier series truncated to the frequency of interest. The latter is then fully sampled and subtracted from the data. We produce individual maps for each of the detectors as well as combined maps per channel using the best available bolometers.

From top to bottom, Fig. 36 shows the combined Galactic maps for the Archeops 143, 217, 353 and 545 GHz channels respectively. These are the first available large angular scales maps of the sky in this frequency range. The maps are displayed in antenna temperature units and in Galactic coordinates with the Galactic anticenter at the center of the map. The Galactic plane structure, including for example the Cygnus region on the right of the map and the Taurus region on the left, are clearly visible. Their intensity increases globally with frequency as expected for Galactic dust emission. At high Galactic latitudes the maps at low frequencies show no contamination from the atmospheric emission. At 545 GHz we can observe some atmospheric contamination. This was expected since the atmospheric signal is stronger at high frequencies and because we have only a single bolometer available. More detailed description and scientific analysis of these maps will be presented in a forthcoming paper. In particular almost all (about 100) identified point sources are Galactic and will be presented elsewhere.

10.3. Specific processing for polarization maps

Whereas most of the preprocessing and noise subtraction is common to all channels, the 353 GHz polarized channel requires additional specific treatments. The direction of polarization of the bolometers oriented mechanically in the focal plane has to be checked, as well as their polarization efficiencies. Moreover, the map making algorithm differs from that of temperature maps since it has to deal with non scalar quantities. Details regarding the map making algorithm as well as the final polarized Archeops maps at 353 GHz are given in Benoît et al. (2004). Previous to map making the TOIs are processed as above using the MCMD-SMICA algorithm to remove the contamination from atmospheric emission.

The reconstruction of the polarization directions of the bolometers in the focal plane was performed during ground calibration. For this purpose, we built two wire grid polarizers of 10 cm diameters with the same technology as the one used for wire chambers in high energy physics experiments. We used Cu/Be wires of 50 microns, spaced by 100 microns on circular steel frames which was expected to produce an incoming radiation at more than 98% at 850 microns (353 GHz). We built an alignment mechanism that could hold one or both polarizers on top of the entrance window of the cryostat, facing directly the focal plane. One of the polarizers could rotate at 1.5 rpm. A 13.4 Hz chopper modulated the incoming radiation of a liquid Nitrogen polystyrene box used as a 77 K black body to enable a lock-in detection. Once the lock-in and standard noise subtraction were performed, the rotating polarizer induced a 1.5 rpm period sinusoidal response for the polarized channels, from which the phase provided the direction in the focal plane, and the offset and amplitude the cross-polarization level. The positions were confirmed to be nominal (30, 120, 150, 240, 90, 0) deg w.r.t. the scan axis up to the precision of the method which was estimated to be 3 deg. The cross polarization, defined as the ratio cross-Intensity/co-Intensity was found to be approximately 2%.

The absolute calibration of the polarized photometers was performed in the same way as for the other channels. The relative calibration was performed using the algorithm described in Sect. 9.4. Actually, it was originally designed for the polarized channels. The only caveat was the possible systematic effect induced by a polarized Galactic component. A two step iteration process was designed, the first of which consisted in the re-

Fig. 36. From top to bottom: Galactic maps in antenna temperature for the 143, 217, 353 and 545 GHz Archeops channels. They are displayed in Galactic coordinates with the Galactic anticenter at the center of the map.

Fig. 37. From top to bottom, power spectrum of the Archeops time ordered data before (black curve) and after (red curve) foreground removal for the 143K03 and 217K04 bolometers respectively. For comparison, the bottom plot shows the power spectrum of the 545K01 bolometer.

Fig. 38. *Top*: Angular power spectrum of the simulated CMB signal before (black line) and after data processing (blue line) for the 143 GHz. *Bottom*: Transfer function of the data processing pipeline for 143 GHz data.

moval of the strong polarized regions before a final relative calibration on the non polarized parts of the Galaxy. This process ensured a relative calibration of the polarized detectors better than 2%. More details can be found in Benoît et al. (2004).

10.4. Specific processing for CMB maps.

10.4.1. Foreground removal

For reconstructing the CMB signal on the sky we need to remove from the Archeops data the foreground contribution corresponding to the Galactic dust emission and the atmospheric parasitic noise. Both of them have a rising electromagnetic spectrum with increasing frequency. Therefore they are significantly brighter in the Archeops high frequency channels. The Galactic dust emission in the millimetre and submillimetre range has a grey body spectrum with an emissivity of the order of between 1.7 and 2 (see Finkbeiner et al (1999), Bennett et al. (2003), Lagache (2003) for more details). A slightly steeper index increasing with frequency is observed for the atmospheric parasitic noise.

We have developed a decorrelation algorithm to remove the foregrounds from the Archeops data. As templates of the foreground emission we have used the Archeops high frequency channel bolometers but also fake timelines of the expected Galactic emission contribution to the Archeops data to improve the efficiency of the algorithm. These fake timelines were produced in two steps. First we extrapolated the IRAS satellite data to the Archeops frequencies using the model 8 of Finkbeiner et al (1999). Second the extrapolated maps were deprojected into time ordered data following the Archeops scanning strategy. For the decorrelation analysis of each of the low frequency (at 143 or 217 GHz) bolometers we used as templates the 353 and 545 GHz time ordered data, fake Galactic timelines corresponding to those data and an extra fake Galactic timeline corresponding to the decorrelated bolometer.

To improve the efficiency of the decorrelation method we bandpass filter both the Archeops data and the fake Galactic timelines in the range 0.1 to 2 Hz where the atmospheric and Galactic emission dominate. This can be clearly seen on the bottom plot of Fig. 37 where we represent the power spectrum of time ordered data for the bolometer 545K01. At low frequency we observe the Galactic and atmospheric emissions in the form of peaks at frequencies which are multiples of the spinning frequency. Between 1 and 1.5 Hz we can distinguish the atmospheric parasitic structure discussed in Sect. 10.2. Above 1.6 Hz the instrumental noise dominates. The correlation coefficients are computed via a simple regression analysis using the bandpass filtered data. A linear combination of the templates previously smoothed and multiplied by the correlation coefficients is removed from the data.

The first two upper plots of Fig. 37 show the results of the decorrelation analysis for the Archeops bolometers 143K03 and 217K04 respectively. We plot the power spectrum of time ordered data before (black curve) and after (red curve) decorrelation. For the 143K03 bolometer we can observe that the peaks in the spectrum are completely removed by the decorrelation analysis but at frequencies lower than 0.2 Hz. The same is found for the 217K04 bolometer. Further, we see that the atmospheric structures between 1 and 1.5 Hz are also removed. The residual Galactic emission at frequencies lower than 2 Hz increases dramatically with decreasing frequency. This seriously limits the size of the largest angular scale for which the CMB angular power spectrum can be reconstructed using the Archeops data. Although the algorithm is very efficient residual atmospheric and Galactic emission are expected in the final Archeops CMB maps. A more detailed discussion of these two issues is given in Tristram et al. (2005b) and Patanchon *et al.* (2005).

10.4.2. The pipeline transfer function

For an accurate determination of the CMB power spectrum with the Archeops data we have to correct from the bias introduced in the signal by the data processing. For this we have estimated the Archeops pipeline transfer function in multipole space. Here we consider the full data processing but the destriping for which the transfer function was discussed above.

For each of the Archeops bolometer at 143 and 217 GHz we have obtained fake Archeops CMB timelines. These were produced from the deprojection, using the Archeops pointing solution, of the same simulated CMB map. These CMB timelines have been converted into voltage units using the standard calibration coefficients for each bolometer and then filtered out with the low pass prefilter (see Sect. 4.1). Further, we have added, to each original bolometer time ordered data, the corresponding fake CMB timeline and then saved them into files

the same way the true ones are. Finally, we have passed each combined timeline through the full Archeops data pipeline but through the destriping. The effect of the data processing on the CMB simulated signal can be easily obtained. First we subtract from the combined processed timeline the corresponding equally processed Archeops data. Finally, we reproject the difference into a map. Comparing the CMB angular power spectrum of the simulated Archeops CMB signal before and after data processing we obtain the pipeline transfer function.

The top panel of Fig. 38 shows the angular power spectrum for the simulated CMB data before (black line) and after (blue line) data processing for one of the 143 GHz Archeops bolometers. Dividing the one by the other we can estimate the Archeops pipeline transfer function which is shown in the bottom panel plot. We observe that the changes induced in the CMB signal by the data processing pipeline are smaller than 1%. Similar results are obtained for the other bolometers at 143 and 217 GHz. Therefore, there is no need to account for the pipeline transfer function when estimating the CMB angular power spectrum with Archeops (see Benoît et al. (2003a), Tristram et al. (2005b)).

10.4.3. Archeops CMB maps

The Archeops CMB maps were obtained by projection and bandpass filtering of the foreground cleaned timelines using the Mirage optimal map making code (Yvon & Mayet (2005)). The data were low pass filtered at 30 Hz to remove spurious high frequency noise and high pass filtered at 0.1 Hz to reduce the contribution from residual atmospheric and Galactic emissions. We have produced both individual maps for each of the selected best bolometers at 143 and 217 GHz, and combined naturally weighted maps for each of the low frequency channels.

Figure 39 shows from top to bottom, the Archeops combined CMB maps at 143 and 217 GHz. These maps are in longitude rotated Galactic coordinates with the anticenter at the center of the maps. We represent them in CMB temperature units. Notice that close to the Galactic center and in particular near by the Cygnus region (right of the map) we can observe residuals from the Galactic emission. However at high Galactic latitude neither atmospheric nor Galactic residuals are observed. For CMB analysis (Benoît et al. (2003a), Tristram et al. (2005b)) we use a Galactic mask to exclude the observed contaminated regions. This mask is overplotted in blue on the figure. A detailed analysis of the properties of these maps and how they compare to those from the WMAP satellite is presented in a forthcoming paper (Patanchon *et al.* (2005)). Other than CMB studies, these maps were used in combination with the WMAP data (Bennett et al. (2003)) to study statistically the Sunyaev-Zeldovich effect in clusters of galaxies (Hernández-Monteagudo et al. (2006)).

11. Conclusions

We have presented in this paper the full processing of the Archeops data, from the raw telemetry to the final sky maps. Despite intense preparatory work, most methods and procedures discussed here were developed and implemented after the acquisition of the real flight data. This was mainly due to the requirement of a large sky coverage in a short total integration time (about 24 hours) which imposed a large-circles like scanning strategy with small redundancy and therefore making systematic effects difficult to handle. Typically the data were contaminated by the large scale fluctuations of the atmospheric emission and by the Galactic foreground emission. Because of these difficulties we were forced to apply different processing techniques to the data for each of the main scientific goals, 1) estimation of the CMB temperature anisotropies power spectrum, 2) study of the Galactic diffuse emission and 3) estimation of the polarized submillimetre emission of the Galaxy. In particular, the destriping and filtering techniques previous to projection on the sky were different for each pipeline leading to different output maps. A common general destriping, based on the assumption that the structures do not have preferred directions on the sky, was applied to data in all pipelines. For CMB maps, the low frequency channels were further decorrelated from a mixture of the high frequency data, which are dominated by atmospheric and Galactic signal. For Galactic maps, the atmospheric component was subtracted using a component separation method on the timelines. For the polarization pipeline simultaneous time and frequency filtering was applied.

The processing and the instrumental setup were improved between successive flights going from the Trapani test flight to the latest Kiruna one. For example, after analysis of the data of the first two flights, we were able to reduce significantly the high frequency noise excess in the data by moving the spinning pivot motor higher up in the flight chain to dampen mechanical vibrations. A thermal dependency of the signal with the 10 K thermal stage was completely removed for the last flight after a complete clean-up of the corrugated back–to–back horns in each of the Archeops photometric pixels. By contrast, because of the wearing off of the instrument from flight to flight and the lack of time for a complete ground calibration, the instrument was not launched in a fully optimal configuration in the latest Kiruna flight. In particular, we are aware that as a consequence of the accidental landing during the penultimate campaign, the telescope was slightly out of focus producing optical beams larger and more elongated than expected. To correct for this asymmetry new specific processing techniques were developed.

The processing of the Archeops data could not be performed in a single linear pipeline. We needed extra pipelines to reconstruct the pointing information, compute basic instrumental and observational parameters. For example with respect to calibration, we had to design dedicated pipelines for each of the method used: dipole reconstruction, Galaxy dust emission, intercalibration, planet calibration. Equally, we have worked in independent pipelines to characterize the instrumental response but also the data processing in order to correct the bias introduced by those effects in the computation of the CMB temperature angular power spectrum and of the polarized dust power spectra. For this purpose we have computed the transfer functions in multipole space for the

Fig. 39. From top to bottom, combined Archeops CMB maps for the 143 and 217 GHz channels. In the Galactic plane region the residual galactic emission is still visible but clearly disappears at high galactic latitudes where the CMB studies are performed.

beam smoothing, the pipeline processing and the destriping. Further, we have produced very specific pipelines to remove foreground contributions on the data for each of the scientific goals. Many checks were performed on the subpipeline levels using simulated data. Complete end-to-end tests were difficult to achieve because of the complexity of the problem and the fact that the pipelines could not be gathered in a single one.

Archeops provides the first submillimetre maps of the sky with large sky coverage, of the order of 30 %, at sub–degree resolution and the large-angular scales of both the CMB temperature anisotropies and the temperature and polarization diffuse emission from Galactic dust. Maps of the temperature diffuse Galactic dust emission are available at the four Archeops frequency channels, 143, 217, 353 and 545 GHz. These are very useful maps as intermediate resolution products between the FIRAS and the expected Planck HFI maps (Bernard (2004)). Foreground-cleaned CMB maps were produced for the lowest frequency channels at 143 and 217 GHz using the information on dust and atmospheric emission provided by the high frequency ones. These maps provided the first simultaneous determination of the Sachs-Wolfe plateau and of the first acoustic peak of the CMB anisotropies temperature power spectrum (Benoît et al. (2003a)) and more recently of the second acoustic peak (Tristram et al. (2005b)). By combining those maps with the data from the WMAP experiment and the 2MASS catalog of galaxies we obtained a local statistical detection of the SZ effect in clusters (Hernández-Monteagudo et al. (2006)). In a forthcoming paper (Patanchon *et al.* (2005)), an analysis of the level of any diffuse SZ emission will be presented, using the Archeops and WMAP data in order to have a broad electromagnetic spectral leverage. Finally, I, Q and U maps of the polarized diffuse emission of Galactic dust were constructed at 353 GHz combining the measurements from the six polarized sensitive bolometers. These maps allowed us, for the first time, to characterize the polarized diffuse emission from Galactic dust in the Galactic plane (Benoît et al. (2004)) and to estimate the polarized power spectra of the diffuse Galactic dust emission at intermediate and high Galactic latitudes (Ponthieu et al. 92005)).

The Archeops data are the first available data which present very similar characteristics to those of the Planck HFI instrument. This is because the instrumental configuration, the acquisition system and the scanning strategy in Archeops and Planck are very similar. There are few important differences between these two data sets as for example the presence of an atmospheric signal in the Archeops data which would not be at all present in the Planck data and which is one of the most important systematics in Archeops. However, in many other aspects they are sufficiently similar to consider that the techniques and methods applied for the processing of the Archeops data will be of great use for processing the Planck HFI data. In this sense, the processing of the Archeops data was for us a learning process towards the analysis of the Planck HFI data. Actually, most of the preprocessing, decorrelation, deconvolution from the bolometer time constant, beam pattern reconstruction, noise spectrum estimation, destriping, calibration and power spectrum estimation methods are currently being adapted to the Planck data within the Planck HFI Level 2 data processing.

We encourage interested parties to contact members of the Archeops collaboration to any specific scientific project (for example correlation with other data sets) using the Archeops data.

Appendix A: Intercalibration procedure

We describe here the details of the intercalibration procedure of the Archeops bolometers discussed in Sect. 9.4.

A.0.4. Modeling

Let's formulate the problem as follows : $s_1(b), \ldots, s_N(b)$ are N profiles (*e.g.* of the Galaxy), measured by N different bolometers; b stands for the Galactic latitude, and runs from 1 to B; $\overline{s}_b$ is the estimated profile, which has to be determined.

We can write the estimated profile as :

$$s_j(b) = \alpha_j \overline{s}(b) + n_j(b) \qquad \text{(A.1)}$$

where $n_j(b)$ is the noise in the bin b of profile j and α_j the associated calibration coefficient.

If we assume Gaussian white noise, we can write the χ^2 as :

$$\chi'^2 = \sum_{j=1}^{N} \sum_{b=1}^{B} \frac{(s_j(b) - \alpha_j \overline{s}(b))^2}{\sigma_j(b)^2} \qquad \text{(A.2)}$$

with $\sigma_j(b)^2$ the noise variance $\langle n_j(b)^2 \rangle$ (we neglect noise correlations between detectors).

A.0.5. Constraint

We notice that the χ^2 is invariant under the following transformation :

$$\left\{ \begin{array}{rcl} s_k(b) & \longrightarrow & \beta \cdot \overline{s}_k(b) \\ \alpha_k & \longrightarrow & \frac{\alpha_k}{\beta} \end{array} \right. \qquad \text{(A.3)}$$

This degree of freedom is due to the fact that we can only determine the intercalibration coefficient up to a constant factor. We must choose a constraint on the parameters in order to converge to a unique solution of the equations.

Let's choose a general relation : $g(\{\alpha_i\}, \{\overline{s}(b)\}) = 0$. Using the method of Lagrange's multiplier, we thus have to minimize the function

$$\chi^2\left(\{\alpha_i\},\{\overline{s}(b)\},\lambda\right) = \chi'^2\left(\{\alpha_i\},\{\overline{s}(b)\}\right) + \lambda g\left(\{\alpha_i\},\{\overline{s}(b)\}\right) \quad (A.4)$$

with respect to $\{\alpha_i\},\{\overline{s}(b)\}$ and λ. The conditions of minimum lead to the three equations :

$$\frac{\partial\chi^2}{\partial\lambda} = 0 \Rightarrow g\left(\{\alpha_i\},\{\overline{s}(b)\}\right) = 0 \quad (A.5)$$

$$\frac{\partial\chi^2}{\partial\overline{s}(b)} = -2\sum_i \frac{\alpha_i(s_i(b)-\alpha_i\overline{s}(b))}{\sigma_{ib}^2} + \lambda\frac{\partial g}{\partial\overline{s}(b)} = 0 \quad (A.6)$$

$$\frac{\partial\chi^2}{\partial\alpha_i} = -2\sum_b \frac{\overline{s}(b)(s_i(b)-\alpha_i\overline{s}(b))}{\sigma_{ib}^2} + \lambda\frac{\partial g}{\partial\alpha_i} = 0 \quad (A.7)$$

Multiplying Eq. (A.6) by $\overline{s}(b)$ and summing over b, and multiplying Eq. (A.7) and summing over i, we find that $\lambda = 0$ is the only solution. We thus find the two following relations :

$$\overline{s}(b) = \frac{\sum_j \frac{\alpha_j s_j(b)}{\sigma_j(b)^2}}{\sum_j \frac{\alpha_j^2}{\sigma_j(b)^2}} \quad (A.8)$$

and

$$\alpha_k = \frac{\sum_b \frac{\overline{s}(b)s_k(b)}{\sigma_k(b)^2}}{\sum_b \frac{\overline{s}(b)^2}{\sigma_k(b)^2}} \quad (A.9)$$

whatever is the constraint.

These equations can be solved by iteration : starting from any set of $\{\alpha_i\}$, we can calculate $\overline{s}(b)$ with Eq. (A.8), and calculate new $\{\alpha_i\}$ with Eq. (A.9). At each step of the iteration, we have to check that the constraint is satisfied, or to impose it. The iteration ends when the relative differences between two successive steps is small enough.

A.0.6. Error matrix

We can develop any χ^2 functions around its minimum as :

$$\chi^2(\mathbf{\Theta}) = \chi^2\left(\mathbf{\Theta}^{(min)}\right) + \frac{1}{2}\frac{\partial^2\chi^2}{\partial\Theta_i\partial\Theta_j}\left(\Theta_i-\Theta_i^{(min)}\right)\left(\Theta_j-\Theta_j^{(min)}\right) + O(\Theta^3) \quad (A.10)$$

where $\mathbf{\Theta}$ is the vector of parameters and $\mathbf{\Theta}^{(min)}$ is the minimum of the χ^2. The matrix $\frac{1}{2}\frac{\partial^2\chi^2}{\partial\Theta_i\partial\Theta_j}$ is called the Fisher matrix (noted F in the following) and is the inverse of the matrix of correlation of the parameters, as can be easily seen : calling $\Delta\mathbf{\Theta}$ the vector $\mathbf{\Theta}-\mathbf{\Theta}^{(min)}$, the probability that the real parameters are Θ can be written using the likelihood function $\mathcal{L} = \exp(-\chi^2/2)$, *i.e.* :

$$\mathcal{L} \propto e^{-\frac{\Delta\mathbf{\Theta}^t\cdot F\cdot\Delta\mathbf{\Theta}}{2}}. \quad (A.11)$$

Since F is a positive definite matrix, it can be diagonalized, with all its eigen values positive. Let's call M the change of frame matrix, so that $F = M^tDM$, where D is diagonal, and $\Delta\Theta' = M\Delta\Theta$. M is orthogonal, so that $M^{-1} = M^t$. The correlation between two measurements will be given by : $\langle\Delta\mathbf{\Theta}\Delta\mathbf{\Theta}^t\rangle = \langle M^t\Delta\mathbf{\Theta}'\Delta\mathbf{\Theta}'^tM\rangle = M^t\langle\Delta\mathbf{\Theta}'\Delta\mathbf{\Theta}'^t\rangle M$. The central part is the correlation matrix in the diagonal frame : it can be calculated directly to give $\langle\Delta\mathbf{\Theta}'\Delta\mathbf{\Theta}'^t\rangle = D^{-1}$. We then deduce the correlation matrix in the original frame : $\langle\Delta\mathbf{\Theta}\Delta\mathbf{\Theta}^t\rangle = M^tD^{-1}M = (M^tDM)^{-1} = F^{-1}$. All this calculation is made with the assumption that the likelihood is very close to a Gaussian around its maximum. We will see in the following that it is the case for our particular case.

In our particular case, the Fisher matrix F is dimension $(N+B+1)\times(N+B+1)$, and we can compute it analytically for any constraint g :

$$\frac{1}{2}\frac{\partial^2\chi^2}{\partial\lambda^2} = 0 \quad (A.12)$$

$$\frac{1}{2}\frac{\partial^2\chi^2}{\partial\lambda\partial\overline{s}(b)} = \frac{\partial g}{\partial\overline{s}(b)} \quad (A.13)$$

$$\frac{1}{2}\frac{\partial^2\chi^2}{\partial\lambda\partial\alpha_i} = \frac{\partial g}{\partial\alpha_i} \quad (A.14)$$

$$\frac{1}{2}\frac{\partial^2\chi^2}{\partial\overline{s}(b)\partial\overline{s}(q)} = \sum_{j=1}^{N}\frac{\alpha_j^2}{\sigma_j(q)^2}\delta_{qb} \quad (A.15)$$

$$\frac{1}{2}\frac{\partial^2\chi^2}{\partial\overline{s}(b)\partial\alpha_k} = \frac{2\alpha_k\overline{s}(b)-s_k(b)}{\sigma_k(b)^2} \quad (A.16)$$

$$\frac{1}{2}\frac{\partial^2\chi^2}{\partial\alpha_i\partial\alpha_j} = \sum_{b=1}^{B}\frac{\overline{s}(b)^2}{\sigma_i(b)^2}\delta_{ij} \quad (A.17)$$

(taking all the parameters at the minimum, including $\lambda = 0$).

Fig. A.1. Simulation profiles

A.0.7. Robustness tests

We have performed a bunch of tests in order to validate this intercalibration method. First, we have tested by Monte Carlo simulations the reliability of the error bars computed using the Fisher matrix. Second, we have compared the influence of the choice of the constraint on the intercalibration coefficients and their errors : when comparing what is comparable, *i.e.* the *ratio* of intercalibration coefficients, we found no difference neither in the value nor in the error. We have chosen to impose the constraint $g(\{\overline{s}(b),\{\alpha_i\}\}) = \alpha_1 - 1$ (*i.e.* the first profile has a relative calibration coefficient with respect to the average profile of 1). Finally, we have compared the iterative minimization method (using alternatively Eqs. A.8 and A.9) with a standard minimization program (Minuit, from the CernLib). Differences were below the numerical precision.

Acknowledgements. We would like to pay tribute to the memory of Pierre Faucon who led the CNES team during several difficult and long campaigns. We thank the Russian recovery teams who worked under very harsh conditions to retrieve the precious instrument and data. The Swedish Kiruna Esrange base is warmly thanked for much help during the launch preparations. We thank the CNES balloon program, Programme National de Cosmologie, and the participating laboratories for financial support. We thank Juan R. Pardo for helping us with atmospheric modeling and Bruno Bézard for planet calibration. The HEALPix package was used throughout the data analysis (Gorski et al. (1999)).

References

Amblard & Hamilton, 2004, A&A, 417, 1189-1194

Bock, J.J., Parikh, M.K., Fischer, M.L.& Lange, E., 1995, Applied Optics, 34, 22

Bennett, C. L., Halpern, M., Hinshaw, G. et al., 2003, ApJ, 148, 1

Benoît, A. & Pujol, S., 1994, Cryogenics, 34, 321

Benoît, A. et al. 2002, Astropart. Phys., 17, 101

Benoît A. et al. 2003, A&A, 399, No. 3, L19

Benoît A. et al. 2003, A&A, 399, No. 3, L25

Benoît, A., et al. 2004, A&A, 424, 571

Bernard, 2004,35th COSPAR Scientific Assembly, 4558

Bourrachot. 2004, Université Paris Sud - Paris XI, http://tel.ccsd.cnrs.fr/documents/archives0/00/00/ 77/02/index_fr.html

Bock, J. J, DelCastillo, H. M., Turner, A. D., Beeman, J. W., Lange, A. E. Mauskopf, P. D., 1996, Proc. of the 30th ESLAB symp. on "Submillimetre and Far-Infrared Space Instrumentation", ESA-ESTEC 1996

Borrill, J., 1999, In *Proceedings of the 5th European SGI/Cray MPP Workshop*, Bologna, Italy, astro-ph/9911389

Camus, Ph., Berg, L., Dumoulin, L., Marnieros, S., & Torre, J.–P. 2000, Nucl. Instr. and Methods in Phys. Res. A444, 419

Cappellini, B. Maino, D., Albetti, G., *et al.* , 2003, A&A, 409, 375

Chattopadhyay, G., *et al.*, 1999, IEEE microwave and guided wave letters

Delabrouille J.,Cardoso J.F., Patanchon,G., 2003, MNRAS, 346, 1089

Dickinson, C. et al. 2004, MNRAS, 353, 732

Doré, O., Teyssier, R., Bouchet, F. R., Vibert, D., & Prunet, S., 2001, A&A, 374, 358

Dragone, C. 1982, IEEE Trans. Ant. Prop., AP-30, No. 3, 331

Ferreira, P. & Jaffe, A. H., 2000, MNRAS, 312, 89

Finkbeiner, Douglas P., Davis, Marc, Schlegel, David J., 1999, ApJ, 524, 867

Fixsen, D. J., Weiland, J. L., Brodd, S., Hauser, M. G., Kelsall, T., Leisawitz, D. T., Mather, J. C., Jensen, K. A., Schafer, R. A., Silverberg, R. F., 1997,ApJ, 490, 482

Goldin, A.B. *et al.*, 1997, ApJ, 488, L161

Gorski K. M., Hivon E. & Wandelt B. D., 1999, in Proceedings of the MPA/ESO Cosmology Conference "Evolution of Large-Scale Structure", eds. A.J. Banday, R.S. Sheth and L. Da Costa, PrintPartners Ipskamp, NL, pp. 37-42 (also astro-ph/9812350, http://www.eso.org/science/healpix)

Halverson, N. W. et al. 2002, ApJ, 545, L5

Hanany, S. et al. 2000, ApJ, 545, L5

Hernández-Monteagudo, C., Macías-Pérez, J.F., Tristram, M. & Desert, F.–X., 2006, A&A, 449, 41

Hinshaw, G. et al., 2003, ApJ, 148, 63

Hivon, E., Gorski, K. M., Netterfield, C. B. et al., 2002, ApJ, 567, 2

Janssen, M. A., & Gulkis, S., Mapping the Sky with the COBE-DMR. In "The Infrared and Submillimetre Sky after COBE", M. Signore and C. Dupraz editors, Dordrecht, Kluwer, 1992

Kuo, C. L. et al. 2004, ApJ, 600, 32

Lagache, G., 2003, A&A, 405, 813L

Lagache, G., Douspis M., A&A, submitted

Lamarre, J.M. et al. 2003, New Astronomy Reviews, 47, 11-12

Lee,A. T. et al., 2001, ApJ, 516, 1L

Macías–Pérez & Bourrachot, A., 2006, A&A, accepted

Masi, S. et al. 2005, ApJ, submitted, astro-ph/0507509

Mason, B. S. et al. 2003, ApJ, 591, 540

Mather, J. C., Fixsen, D. J., Shafer, R. A., *et al.* , 1999, ApJ, 512, 511

Mather, J. C.,Cheng, E. S., Shafer, R. A., Wright, E. L., Meyer, S. S., Weiss, R., Fixsen, D. J., Eplee, R. E., Isaacman, R. B., Read, S. M., 1990, BAAS, 22, 1216

Mather, J. C., 1984, Applied Optics, 23, 584

Moreno, R., PhD Thesis, ParisVI University

Mizuguchi, Y., Akagawa, M., & Yokoi, H., 1978, Elect. Comm. in Japan, 61-B, No. 3, 58

Nati, F., de Bernardis, P., Iacoangeli, A., Masi, S., Benoit, A., Yvon, D., 2003, Review of Scientific Instruments, 74, 4169

Netterfield, C. B. et al. 2002, ApJ, 568, 38

Pardo, J., Cernicharo, J., Serabyn, E., 2002, Astronomical Site Evaluation in the Visible and Radio Range. ASP Conference Proceedings, Vol. 266. Edited by J. Vernin, Z. Benkhaldoun, and C. Muñoz-Tuñón, Astronomical Society of the Pacific, p.188

Piat, M., Torre, J.-P., Lamarre, J.-M., Beeman, J., Bathia, R.S., 2001, Journal of Low Temperature Physics, 125, 5–6

Piat, M., Lagache, G., Bernard, J.P., Giard, M., Puget, J.-L., 2003, A&A, 393, 359

Patanchon, G., Tristram, M., Macías-Pérez, J.F. *et al*, 2005, A&A, in preparation

Press, W. H., Flannery, B. P., Teukolsky, S. A. & Vetterling, W. T., *Numerical Recipe*, Cambridge University Press, 1992

Ponthieu, N., Macías–Pérez, J. M., Tristram, M., et al, 2005, A&A, 444, 327

Prunet, S., Netterfield, C. B., Hivon, E. & Crill, B. P., In *Proceedings of the XXXVth Rencontres de Moriond, Energy densities in the Universe.* Edition Frontières, 2000, astro-ph/0006052

Rabii, B. et al. 2005, ApJ, submitted, astro-ph/0309414

Ruhl, J. E. et al. 2003, ApJ, 599, 786

Smoot, G. F. et al. 1992, ApJ, 371, L1

Smoot, G. F. et al. 1992, ApJ, 395, L1

Stompor, R.. et al. 2002, Phys. Rev. D, 65, 2, 22003

Tristram, M., Hamilton, J.-Ch., Macías-Peréz, J. F. et al., 2004, Phys. Rev. D, 69, 123008

Tristram, M., Macías-Peréz, J. F., Renault, C. et al., 2005, MNRAS, 358, 833

Tristram, M., Patanchon, G., Macías-Pérez, J.F. et al. 2005, A&A, 436, 785

Yvon D. & Mayet F., 2005, A&A, 436, 729

[1] Laboratoire de Physique Subatomique et de Cosmologie, 53 Avenue des Martyrs, 38026 Grenoble Cedex, France

[2] Department of Physics & Astronomy, University of British Columbia, Vancouver, Canada

[3] Cardiff University, Physics Department, PO Box 913, 5, The Parade, Cardiff, CF24 3YB, UK

[4] University of California, Berkeley, Dept. of Astronomy, 601 Campbell Hall, Berkeley, CA 94720-3411, U.S.A.

[5] Laboratoire de l'Accélérateur Linéaire, BP 34, Campus Orsay, 91898 Orsay Cedex, France

[6] CEA-CE Saclay, DAPNIA, Service de Physique des Particules, Bat 141, F-91191 Gif sur Yvette Cedex, France

[7] APC, 11 pl. M. Berthelot, F-75231 Paris Cedex 5, France

[8] Centre de Recherche sur les Très Basses Températures, BP166, 38042 Grenoble Cedex 9, France
[9] Centre d'Étude Spatiale des Rayonnements, BP 4346, 31028 Toulouse Cedex 4, France
[10] Laboratoire d'Astrophysique de Tarbes Toulouse, 14 Avenue E. Belin, 31400 Toulouse, France
[11] California Institute of Technology, 105-24 Caltech, 1201 East California Blvd, Pasadena CA 91125, USA
[12] Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, California 91109, USA
[13] Institut d'Astrophysique de Paris, 98bis, Boulevard Arago, 75014 Paris, France
[14] CNRS–ENST 46, rue Barrault, 75634 Paris, France
[15] Gruppo di Cosmologia Sperimentale, Dipart. di Fisica, Univ. 'La Sapienza', P. A. Moro, 2, 00185 Roma, Italy
[16] Laboratoire d'Astrophysique, Obs. de Grenoble, BP 53, 38041 Grenoble Cedex 9, France
[17] CSNSM–IN2P3, Bt 108, 91405 Orsay Campus, France
[18] CEA-CE Saclay, DAPNIA, Service d'Astrophysique, Bat 709, F-91191 Gif sur Yvette Cedex, France
[19] Instituto de Ciencias del Espacio (IEEC/CSIC), Facultad de Ciencias, Campus UAB, E-08193 Cerdanyola, Spain
[20] Institut d'Astrophysique Spatiale, Bât. 121, Université Paris XI, 91405 Orsay Cedex, France
[21] LPNHE, Universités Paris VI et Paris VII, 4 place Jussieu, Tour 33, 75252 Paris Cedex 05, France
[22] School of Physics and Astronomy, 116 Church St. S.E., University of Minnesota, Minneapolis MN 55455, USA
[23] LERMA, Observatoire de Paris, 61 Av. de l'Observatoire, 75014 Paris, France
[24] IROE-CNR, Firenze, Italy
[25] ESTEC, Noordwijk, The Netherlands
[26] Experimental Physics, National University of Ireland, Maynooth, Ireland
[27] Dpt of Astrophysical Sciences, Princeton University, Princeton, NJ08544 USA
[28] Landau Institute for Theoretical Physics, 119334 Moscow, Russia
[29] Space Research Institute, Profsoyuznaya St. 84/32, Moscow, Russia
[30] CITA, University of Toronto, 60 St George Street, Toronto, ON M5S 3H8, Canada

Fig. 1. Adiabatic exponent Γ_1. Γ_1 is plotted as a function of lg internal energy [erg g^{-1}] and lg density [g cm^{-3}].

Introduction

In the *nucleated instability* (also called core instability) hypothesis of giant planet formation, a critical mass for static core envelope protoplanets has been found. Mizuno (1980) determined the critical mass of the core to be about 12 $M_\oplus$ ($M_\oplus = 5.975 \times 10^{27}$ g is the Earth mass), which is independent of the outer boundary conditions and therefore independent of the location in the solar nebula. This critical value for the core mass corresponds closely to the cores of today's giant planets.

Although no hydrodynamical study has been available many workers conjectured that a collapse or rapid contraction will ensue after accumulating the critical mass. The main motivation for this article is to investigate the stability of the static envelope at the critical mass. With this aim the local, linear stability of static radiative gas spheres is investigated on the basis of Baker's (1966) standard one-zone model.

Phenomena similar to the ones described above for giant planet formation have been found in hydrodynamical models concerning star formation where protostellar cores explode (Tscharnuter 1987, Balluch 1988), whereas earlier studies found quasi-steady collapse flows. The similarities in the (micro)physics, i.e., constitutive relations of protostellar cores and protogiant planets serve as a further motivation for this study.

1. Baker's standard one-zone model

In this section the one-zone model of Baker (1966), originally used to study the Cepheïd pulsation mechanism, will be briefly reviewed. The resulting stability criteria will be rewritten in terms of local state variables, local timescales and constitutive relations.

Baker (1966) investigates the stability of thin layers in self-gravitating, spherical gas clouds with the following properties:

- hydrostatic equilibrium,
- thermal equilibrium,
- energy transport by grey radiation diffusion.

For the one-zone-model Baker obtains necessary conditions for dynamical, secular and vibrational (or pulsational) stability (Eqs. (34a, b, c) in Baker 1966). Using Baker's notation:

M_r mass internal to the radius r
m mass of the zone
r_0 unperturbed zone radius
ρ_0 unperturbed density in the zone
T_0 unperturbed temperature in the zone
L_{r0} unperturbed luminosity
E_{th} thermal energy of the zone

and with the definitions of the *local cooling time* (see Fig. 1)

$$\tau_{\mathrm{co}} = \frac{E_{\mathrm{th}}}{L_{r0}}\,, \tag{1}$$

and the *local free-fall time*

$$\tau_{\mathrm{ff}} = \sqrt{\frac{3\pi}{32G}\frac{4\pi r_0^3}{3M_{\mathrm{r}}}}\,, \tag{2}$$

Baker's K and σ_0 have the following form:

$$\sigma_0 = \frac{\pi}{\sqrt{8}}\frac{1}{\tau_{\mathrm{ff}}} \tag{3}$$

$$K = \frac{\sqrt{32}}{\pi}\frac{1}{\delta}\frac{\tau_{\mathrm{ff}}}{\tau_{\mathrm{co}}}\,; \tag{4}$$

where $E_{\mathrm{th}} \approx m(P_0/\rho_0)$ has been used and

$$\begin{array}{l} \delta = -\left(\frac{\partial \ln\rho}{\partial \ln T}\right)_P \\ e = mc^2 \end{array} \tag{5}$$

Table 1. Opacity sources.

Source	$T/[\mathrm{K}]$
Yorke 1979, Yorke 1980a	≤ 1700[a]
Krügel 1971	$1700 \leq T \leq 5000$
Cox & Stewart 1969	$5000 \leq$

[a] This is footnote a

is a thermodynamical quantity which is of order 1 and equal to 1 for nonreacting mixtures of classical perfect gases. The physical meaning of σ_0 and K is clearly visible in the equations above. σ_0 represents a frequency of the order one per free-fall time. K is proportional to the ratio of the free-fall time and the cooling time. Substituting into Baker's criteria, using thermodynamic identities and definitions of thermodynamic quantities,

$$\Gamma_1 = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_S \ , \ \chi_\rho = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_T \ , \ \kappa_P = \left(\frac{\partial \ln \kappa}{\partial \ln P}\right)_T$$

$$\nabla_{\mathrm{ad}} = \left(\frac{\partial \ln T}{\partial \ln P}\right)_S \ , \ \chi_T = \left(\frac{\partial \ln P}{\partial \ln T}\right)_\rho \ , \ \kappa_T = \left(\frac{\partial \ln \kappa}{\partial \ln T}\right)_T$$

one obtains, after some pages of algebra, the conditions for *stability* given below:

$$\frac{\pi^2}{8}\frac{1}{\tau_{\mathrm{ff}}^2}(3\Gamma_1 - 4) \ > \ 0 \tag{6}$$

$$\frac{\pi^2}{\tau_{\mathrm{co}}\tau_{\mathrm{ff}}^2}\Gamma_1\nabla_{\mathrm{ad}}\left[\frac{1-3/4\chi_\rho}{\chi_T}(\kappa_T - 4) + \kappa_P + 1\right] \ > \ 0 \tag{7}$$

$$\frac{\pi^2}{4}\frac{3}{\tau_{\mathrm{co}}\tau_{\mathrm{ff}}^2}\Gamma_1^2\,\nabla_{\mathrm{ad}}\left[4\nabla_{\mathrm{ad}} - (\nabla_{\mathrm{ad}}\kappa_T + \kappa_P) - \frac{4}{3\Gamma_1}\right] \ > \ 0 \tag{8}$$

For a physical discussion of the stability criteria see Baker (1966) or Cox (1980).

We observe that these criteria for dynamical, secular and vibrational stability, respectively, can be factorized into

1. a factor containing local timescales only,
2. a factor containing only constitutive relations and their derivatives.

The first factors, depending on only timescales, are positive by definition. The signs of the left hand sides of the inequalities (6), (7) and (8) therefore depend exclusively on the second factors containing the constitutive relations. Since they depend only on state variables, the stability criteria themselves are *functions of the thermodynamic state in the local zone*. The one-zone stability can therefore be determined from a simple equation of state, given for example, as a function of density and temperature. Once the microphysics, i.e. the thermodynamics and opacities (see Table 1), are specified (in practice by specifying a chemical composition) the one-zone stability can be inferred if the thermodynamic state is specified. The zone – or in other words the layer – will be stable or unstable in whatever object it is imbedded as long as it satisfies the one-zone-model assumptions. Only the specific growth rates (depending upon the time scales) will be different for layers in different objects.

We will now write down the sign (and therefore stability) determining parts of the left-hand sides of the inequalities (6), (7) and (8) and thereby obtain *stability equations of state*.

The sign determining part of inequality (6) is $3\Gamma_1 - 4$ and it reduces to the criterion for dynamical stability

$$\Gamma_1 > \frac{4}{3} \ . \tag{9}$$

Stability of the thermodynamical equilibrium demands

$$\chi_\rho > 0, \quad c_v > 0 \, , \tag{10}$$

and

$$\chi_T > 0 \tag{11}$$

Fig. 2. Vibrational stability equation of state $S_{\text{vib}}(\lg e, \lg\rho)$. >0 means vibrational stability.

holds for a wide range of physical situations. With

$$\Gamma_3 - 1 = \frac{P}{\rho T}\frac{\chi_T}{c_v} > 0 \tag{12}$$

$$\Gamma_1 = \chi_\rho + \chi_T(\Gamma_3 - 1) > 0 \tag{13}$$

$$\nabla_{\text{ad}} = \frac{\Gamma_3 - 1}{\Gamma_1} > 0 \tag{14}$$

we find the sign determining terms in inequalities (7) and (8) respectively and obtain the following form of the criteria for dynamical, secular and vibrational *stability*, respectively:

$$3\Gamma_1 - 4 =: S_{\text{dyn}} > 0 \tag{15}$$

$$\frac{1 - 3/4\chi_\rho}{\chi_T}(\kappa_T - 4) + \kappa_P + 1 =: S_{\text{sec}} > 0 \tag{16}$$

$$4\nabla_{\text{ad}} - (\nabla_{\text{ad}}\kappa_T + \kappa_P) - \frac{4}{3\Gamma_1} =: S_{\text{vib}} > 0\,. \tag{17}$$

The constitutive relations are to be evaluated for the unperturbed thermodynamic state (say (ρ_0, T_0)) of the zone. We see that the one-zone stability of the layer depends only on the constitutive relations Γ_1, ∇_{ad}, χ_T, χ_ρ, κ_P, κ_T. These depend only on the unperturbed thermodynamical state of the layer. Therefore the above relations define the one-zone-stability equations of state S_{dyn}, S_{sec} and S_{vib}. See Fig. 2 for a picture of S_{vib}. Regions of secular instability are listed in Table 1.

2. Conclusions

1. The conditions for the stability of static, radiative layers in gas spheres, as described by Baker's (1966) standard one-zone model, can be expressed as stability equations of state. These stability equations of state depend only on the local thermodynamic state of the layer.
2. If the constitutive relations – equations of state and Rosseland mean opacities – are specified, the stability equations of state can be evaluated without specifying properties of the layer.
3. For solar composition gas the κ-mechanism is working in the regions of the ice and dust features in the opacities, the H_2 dissociation and the combined H, first He ionization zone, as indicated by vibrational instability. These regions of instability are much larger in extent and degree of instability than the second He ionization zone that drives the Cepheïd pulsations.

Acknowledgements. Part of this work was supported by the German *Deutsche Forschungsgemeinschaft, DFG* project number Ts 17/2–1.

References

Baker, N. 1966, in Stellar Evolution, ed. R. F. Stein,& A. G. W. Cameron (Plenum, New York) 333
Balluch, M. 1988, A&A, 200, 58
Cox, J. P. 1980, Theory of Stellar Pulsation (Princeton University Press, Princeton) 165
Cox, A. N.,& Stewart, J. N. 1969, Academia Nauk, Scientific Information 15, 1
Mizuno H. 1980, Prog. Theor. Phys., 64, 544
Tscharnuter W. M. 1987, A&A, 188, 55
Terlevich, R. 1992, in ASP Conf. Ser. 31, Relationships between Active Galactic Nuclei and Starburst Galaxies, ed. A. V. Filippenko, 13
Yorke, H. W. 1980a, A&A, 86, 286
Zheng, W., Davidsen, A. F., Tytler, D. & Kriss, G. A. 1997, preprint